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NATURE AND TECHNOLOGY OF GEOTHERMAL ENERGY: A REVIEW

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Abstract—Geothermal energy is the energy contained as heat in the Earth's interior. The paper describes the internal structure of the Earth together with the heat transfer mechanisms inside the mantle and crust. It also shows the location of geothermal fields on specific areas of the Earth. The Earth's heat flow and geothermal gradient are defined, as well as the types of geothermal fields, the geologic environment of geothermal energy, and the methods for geothermal exploration.

Geothermal energy, as natural steam and hot water, has been exploited for decades to generate electricity, both in space heating and industrial processes. The geothermal electrical installed capacity in the world is 7173.5 MW_e (December 1996), and the electrical energy generated is 38 billion kW h/year, representing 0.4% of the world total electrical energy which was 13,267 billion kWh in 1995. The thermal capacity in non-electrical uses (greenhouses, aquaculture, district heating, industrial processes) is 8664 MW_t (end of 1994). Electricity is produced with an efficiency of 10–17%, and the geothermal kWh is generally cost-competitive with conventional sources of energy, in the range 3–12 US cents/kWh. The geothermal electrical capacity installed in the world is probably comparable with that from biomass, but almost twice that from solar or wind sources summed together. In developing countries, where total installed electrical power is still low, geothermal energy can play a significant role: in El Salvador 15% of electricity comes from geothermal steam, 15% in Nicaragua, 21% in the Philippines, and 6% in Kenya and Costa Rica.

Financial investments in geothermal electrical and non-electrical uses worldwide are summarised. Present technology makes it possible to control the environmental impact of geothermal exploitation.

The future use of the geothermal energy from advanced technologies such as the exploitation of geopressured reservoirs, hot dry rock systems and magma bodies is briefly discussed. While the viability of hot dry rock technology has been proved, research and development are still necessary for the other two sources.

Finally, a brief discussion follows on training of specialists, geothermal literature, on-line information, and geothermal associations. © 1997 Published by Elsevier Science Ltd

INTRODUCTION

Geothermal energy is the energy contained as heat in the Earth's interior. The origin of this heat is linked with the internal structure of our planet and the physical processes occurring

there. Despite the fact that this heat is present in huge, practically inexhaustible quantities in the Earth's crust, not to mention the deeper parts of our planet, it is unevenly distributed, seldom concentrated, and often at depths too great to be exploited industrially.

The heat moves from the Earth's interior toward the surface where it dissipates, although this fact is generally not noticed. We are aware of its existence because the temperature of rocks increases with depth, proving that a geothermal gradient exists: this gradient averages 30°C/km of depth.

There are, however, areas of the Earth's crust that are accessible by drilling, and where the gradient is well above the average. This occurs when, not far from the surface (a few kilometres) there are magma bodies undergoing cooling, still in a fluid state or in the process of solidification, and releasing heat. In other areas, where magmatic activity does not exist, the heat accumulation is due to particular geological conditions of the crust such that the geothermal gradient reaches anomalously high values.

The extraction and utilisation of this large quantity of heat requires a carrier to transfer the heat toward accessible depths beneath the Earth's surface. Generally the heat is transferred from depth to subsurface regions firstly by conduction and then by convection, with geothermal fluids acting as the carrier in this case. These fluids are essentially rainwater that has penetrated into the Earth's crust from the recharge areas, has been heated on contact with the hot rocks, and has accumulated in aquifers*, occasionally at high pressures and temperatures (up to above 300°C). These aquifers (reservoirs) are the essential parts of most geothermal fields.

In most cases the reservoir is covered with impermeable rocks that prevent the hot fluids from easily reaching the surface and keep them under pressure. We can obtain industrial production of superheated steam or steam mixed with water, or hot water only, depending on the hydrogeological situation and the temperature of the rocks present (Fig. 1).

Wells are drilled into the reservoir to extract the hot fluids, and their use depends on the temperature and pressure of the fluids: generation of electricity (the most important of the so-called high-temperature uses), or for space heating and industrial processes (low-temperature uses).

Geothermal fields, as opposed to hydrocarbon fields, are generally systems with a continuous circulation of heat and fluid, where fluid enters the reservoir from the recharge zones and leaves through discharge areas (hot springs, wells). During industrial exploitation fluids are recharged to the reservoir by reinjecting the waste fluids from the utilisation plants through wells. This reinjection process may compensate for at least part of the fluid extracted by production, and will to a certain limit prolong the commercial lifetime of the field. Geothermal energy is therefore to some extent a renewable energy source, although hot fluid productions rates tend to be much larger than recharge rates.

THE EARTH'S STRUCTURE AND THE PLATE TECTONIC THEORY

The Earth's structure

The Earth is formed by three concentric zones: crust, mantle, and core (Fig. 2).

Crust. The Earth's crust is analogous to the skin of an apple. The thickness of the crust

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* Aquifers are bodies of rocks and/or sediments sufficiently permeable to store and conduct significant amounts of fluids.

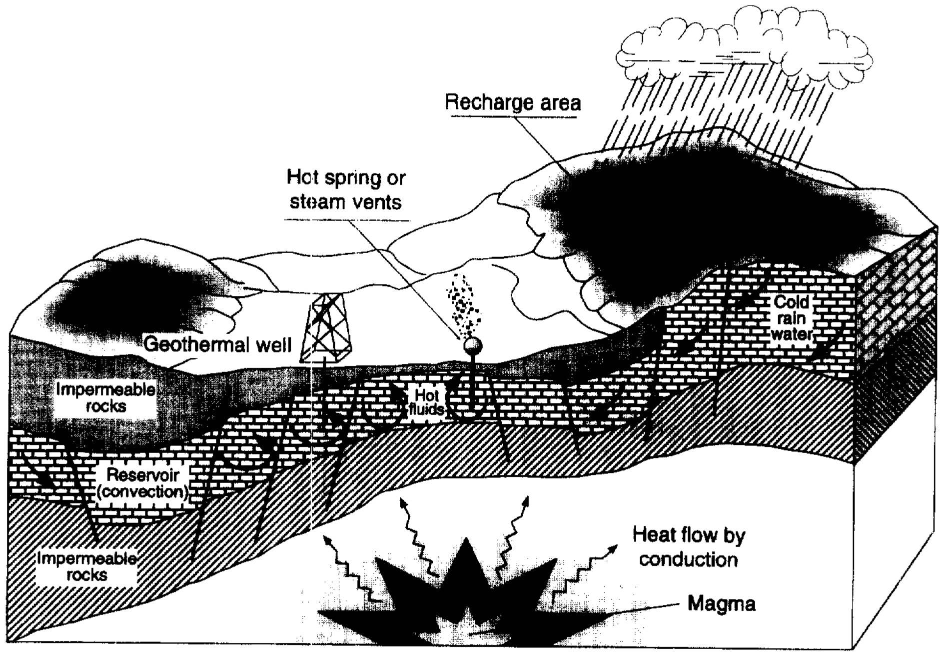

Fig. 1. A geothermal steam field with its elements: recharge area, impermeable cover, reservoir and heat source.

(7 km on average under the ocean basins, 20–65 km under the continents) is insignificant compared to the rest of the Earth which has a polar radius of 6357 km and an equatorial radius of 6378 km.

Wells give us direct access only to the crust, and to depths not much beyond 10 km. Studies of seismic waves have shown that the Earth's crust is thinner beneath the oceans than beneath the continents, and that seismic waves travel faster in oceanic crust than in continental crust. In part because of this difference in velocity, it is assumed that the two types of crust are made up of different kinds of rock. The denser, oceanic crust is made of basalt*, whereas the continental crust is often referred to as being largely granite.

Mantle. The mantle lies closer to the Earth's surface beneath the ocean (at a depth of 7 km) than it does beneath the continents (20–65 km). It extends from the base of the crust for about 2900 km. Because of the way seismic waves pass through the mantle, it is believed that the mantle, like the crust, is solid (though localised magma chambers may occur as isolated liquid pockets in both the crust and the upper mantle), and is probably composed of rock not very different from some kinds of dense rock found at the Earth's surface. The most accepted hypothesis about the composition of the mantle is that it consists of ultrabasic rock (very rich in Fe and Mg) such as *peridotite*, which is a heavy igneous rock made up chiefly of ferromagnesian minerals.

* Basalt is a volcanic rock with low SiO_2 content (45–50%), rich in heavy elements such as Fe and Mg. Basaltic rocks represent more than 90% of the lava flows of the Earth. Granites occur exclusively as intrusive bodies, and contain a high proportion of silica, often more than 70%. In the classification of igneous rocks granites are the rocks richest in silica, just the opposite of basalts.

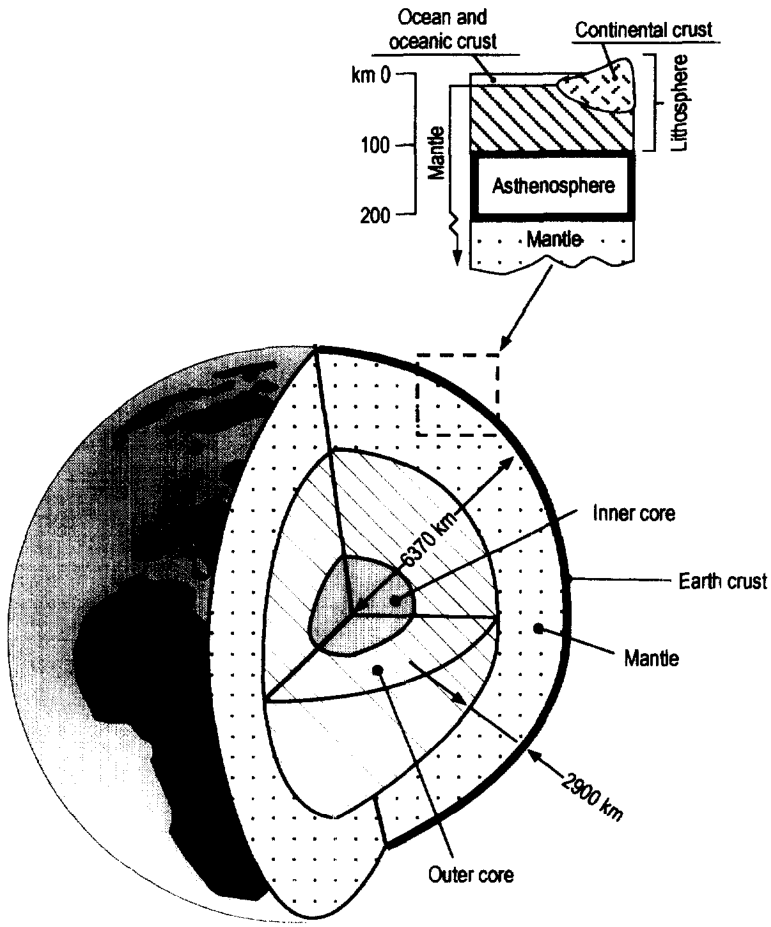

Fig. 2. The Earth's crust, mantle, and core. Top right: a section through the crust and the uppermost mantle. (From Ref. [1], modified.)

The Earth's crust and uppermost mantle together form the *lithosphere*, the outer shell of the Earth that is relatively rigid and brittle (Fig. 2). The lithosphere is split into a number of large blocks at continental scale or more, which are called lithospheric plates in the plate tectonic theory.

The lithosphere (crust and upper mantle) is about 70 km thick beneath the oceans and 100–125 km thick beneath the continents [1]. Its lower boundary inside the mantle is marked by a particular layer, known as the low-velocity zone, in which seismic waves slow down. This zone, extending to a depth of perhaps 200 km (or more) from the surface, is called the *asthenosphere*. Rocks in the asthenosphere may be closer to their melting point than rocks above or below this zone. Where the rocks of the asthenosphere are indeed close to their melting point, this zone becomes important for two reasons:

- it may represent a zone where magma is likely to be generated;
- the rocks there may be weaker and likely to behave plastically.

If mantle rocks in the asthenosphere are weaker than they are in the overlying lithosphere, then the asthenosphere can deform easily by plastic flow, and convection can take place within the asthenosphere as well as within the lower mantle.

The lithosphere seems to be in continual movement, probably as a result of the underlying mantle convection, and plates of brittle lithosphere probably move easily over the asthenosphere, which may act as a lubricating layer below.

Core. The Earth's core extends from 2900 to 6370 km (the Earth's centre): its thickness, or radius, is 3470 km. Calculations show that the core must have a density of about 10 g/cm^3 at the core–mantle boundary, increasing to 12–13 g/cm^3 at the centre of the Earth. This great density would be enough to give the Earth an average density of 5.5 g/cm^3 (by comparison, the density of the crust is between 2.7 g/cm^3 for granite and 2.9 g/cm^3 for basalt, that of the mantle between 3.3 g/cm^3 in the upper mantle and 5.5 g/cm^3 at the base of the mantle) [1]. The temperature in the core should be around 4000°C and the pressure at the Earth's centre 3.6 million bars (360,000 MPa). By comparison, the outer temperature of the Sun is 6000°C, and that of the interior should be around 15 million °C.

The plate tectonic theory

The plate tectonic theory, currently accepted by most geologists, is a unifying theory that accounts for many apparently unrelated geological phenomena. According to this theory the rigid outer shell of the Earth, or lithosphere (crust and upper mantle, thickness in the range 70–100/125 km), is divided into separate blocks or plates, termed *lithospheric plates* (Fig. 3). These plates move slowly across the Earth's surface, at a speed of a few centimetres per year. As the plates comprise both continents and sea floors, the plate tectonics concept means that the continents and sea floors are moving, sliding on top of the underlying plastic asthenosphere. These plates either pull away from each other, slide past each other, or move towards each other.

The boundaries between plates are of three types (Fig. 4):

- *Diverging* plate boundaries (or spreading centres, or ocean ridges). These occur where two plates are moving apart, thus permitting the upwelling of magma from the asthenosphere to form new lithosphere. Most spreading centres coincide with the crest of submarine mountain ranges, called mid-oceanic ridges which rarely rise above sea level (for example, Iceland).
- *Converging* plate boundaries. These correspond to oceanic trenches, where two plates converge and collide so that one plate slips and sinks below the other and is eventually reabsorbed into the mantle and "destroyed" (for example, the Nazca plate in the eastern Pacific Ocean). Convergence occurs when one plate is made of oceanic crust and the other of continental crust. The less dense, more buoyant, continental plate will override the denser oceanic plate. The oceanic plate sinks along what is known as a *subduction zone*, where an oceanic plate descends into the mantle beneath an overriding plate. The entire oceanic plate becomes hotter as it descends deeper into the Earth's interior and melts down.
- *Conservative* plate boundaries. These are faults where two plates slide past each other, so that no lithosphere is either created or destroyed. In this case, the direction of relative motion of the two plates is parallel to the fault. Conservative plate boundaries occur within both the oceanic and continental lithosphere, but the most common conservative plate boundaries are oceanic transform faults (e.g. the San Andreas fault in California; the earthquakes along the fault are the results of plate motion).

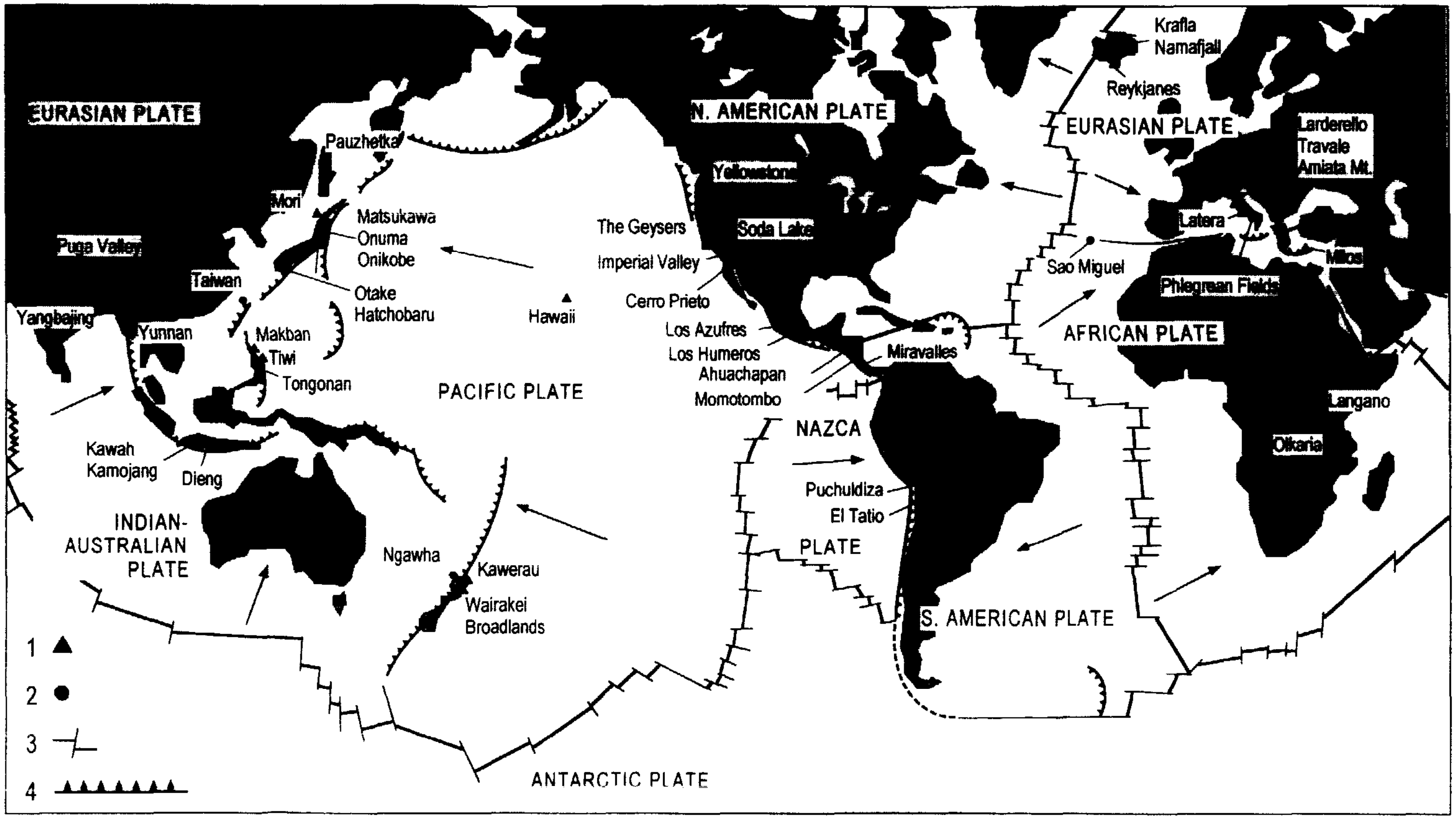

Fig. 3. World pattern of plates, occanic ridges, oceanic trenches, subduction zones, and geothermal fields. Arrows show the direction of movement of the plates towards the subduction zones. (1) Geothermal fields producing electricity; (2) identified high-temperature fields; (3) mid-oceanic ridges crossed by transform faults (long transversal fractures); (4) subduction zones, where the subducting plate bends downwards and melts in the asthenosphere.

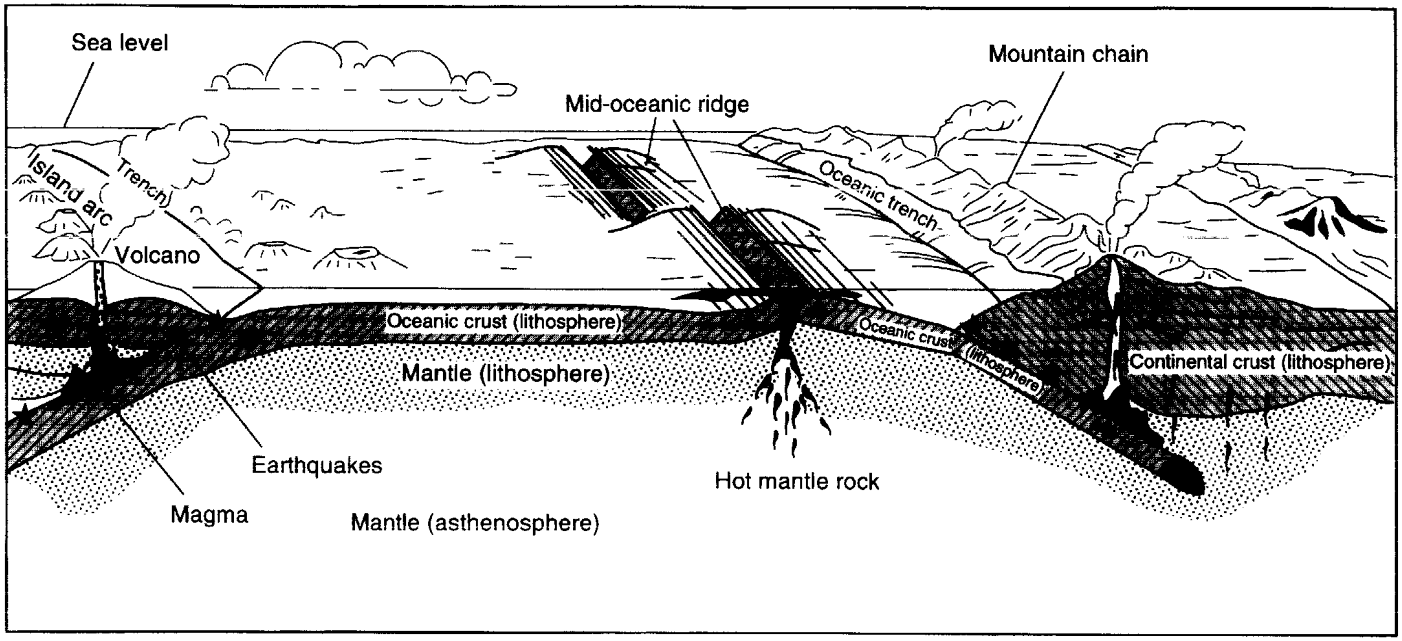

Fig. 4. The basic concept of plate tectonics. Plates of rigid lithosphere (which include the oceanic or the continental crust, and the uppermost mantle), 70–125 km thick, overlie a layer of relatively low strength called the asthenosphere. Mantle material rises below diverging plate boundaries (oceanic ridges), and plate material descends into the mantle at converging plate boundaries (oceanic trenches).

The different types of plate boundaries were originally distinguished on the basis of their *seismicity*. Earthquakes commonly occur at the boundaries of plates, and only occasionally in the middle of a plate. There is a close correspondence between plate boundaries and earthquake belts.

We have already seen that plate tectonic processes are linked to mass movement in the mantle. Because such movement can only occur within materials that have the properties of fluids, this implies that the mantle shows some form of fluid behavior.

THE EARTH'S HEAT FLOW, THE GEOTHERMAL GRADIENT AND THE THERMAL CONDUCTIVITY OF ROCKS

The Earth's heat flow

Our ancestors were well aware that the Earth's interior was hot. The Latin poet Ovid in Book XV of his *Metamorphoses* (verses 342–343), written about 3 AD, has the philosopher and mathematician Pythagoras (who lived 500 years before him) declare that there is a great fire in the Earth's interior, and that this fire is manifest at the surface in the form of volcanoes. The first systematic measurements of temperature underground are accredited to the British chemist Robert Boyle, well known for his gas law. In 1671 Boyle wrote of the heat, sometimes very strong, noted in the mines of Britain, and stated that temperature increases with depth. This phenomenon was reappraised in 1846 by young William Thomson, later Lord Kelvin, one of the fathers of thermodynamics, who, in his PhD thesis at the University of Glasgow, tried to estimate the age of the Earth from the "distribution and movement of heat within it" [2]. However, it was not until 1882 that the values obtained for the geothermal gradient and the thermal conductivity of rocks were combined by Lord Kelvin (their product gives the heat flow) to obtain the heat flow in Great Britain [3].

The Earth's heat flow is the amount of heat that is released into space from the interior through a unit area in a unit of time. It varies from place to place on the surface, and it has varied with time at any particular place during the history of our planet. It is measured in milliwatts per square metre.

The Earth's heat flow originates from the primordial heat, which is the heat generated during the Earth's formation, and from the heat generated since the Earth's formation by the decay of long-lived radioactive isotopes.

Until quite recently, it was supposed that primordial heat was the only source of heat within the Earth. We now know that another major source of heat is the decay of long-lived radioactive isotopes. Although all radioactive isotopes generate heat as they decay, only isotopes that are relatively abundant and have half-lives comparable to the age of the Earth (4.5 billion years) have been significant heat producers throughout geological time and remain so at present. Four long-lived radioactive isotopes are important heat producers: ^{40}K, ^{232}Th, ^{235}U, and ^{238}U.

The average heat flow from continental crust (granite) is 57 mW/m^2, and through oceanic crust (basalt) is 99 mW/m^2. The Earth's average heat flow is 82 mW/m^2, and the total global output is over 4×10^{13} W [4], four times more than the present world energy consumption which is 10^{13} W [5]. Continental heat flow appears to be derived from radiogenic decay within the upper crust, together with the heat generated in the most recent magmatic episode and the heat coming from mantle. In the oceanic crust, the concentration of radioactive isotopes is so low that radiogenic heating is negligible, and the heat flow largely derives from heat flowing from the mantle below the lithosphere.

We know that:

- in the *continental crust*, the heat flow at the surface is highest in areas that have experienced magmatic or metamorphic activity more recently than 65 million years (from Cenozoic to present, 77 mW/m^2), and that heat flow decreases to a constant value of about 46 mW/m^2 in crust older than 800 million years (Precambrian).
- in the young *oceanic crust* (< 65 million years, from Cenozoic to present) heat flow is higher and more variable (70–170 mW/m^2) than in older oceanic crust (> 65 million years), which has lower and more constant heat flow (about 50 mW/m^2). The heat flow decreases with age of the oceanic crust [4].

Heat transfer within the Earth

The Earth's conductive heat flow is the product of the geothermal gradient and the thermal conductivity of rocks. The geothermal gradient is measured in shallow holes, while the conductivity of rocks is best measured in the laboratory on samples (called cores) taken from that part of the well where the gradient was measured.

Two forms of heat transfer occur within the Earth: conduction and convection.

- *Conduction*. Conduction involves the transfer of random kinetic energy between molecules without the overall transfer of material. Moving molecules strike neighbouring molecules, causing them to vibrate faster and thus transfer heat energy. Conduction is the primary heat transfer mode in solids. Metals are very good conductors of heat, whereas most rocks are relatively poor conductors.
- *Convection*. Convection is the common heat transfer process in liquids or gases and consists of the movement of hot fluid (i.e. a liquid or a gas) from one place to another. Because motion of material occurs, convection is a vastly more efficient process of heat transfer than conduction. In a kettle of water placed over a fire, hot water heated by the fire at the bottom of the kettle rises to the surface near the centre and then, as it cools, returns to the bottom of the kettle to be heated again. The resulting circulation, or convection pattern, eventually heats all the water in the kettle.

The geothermal gradient

Studies of the thermal behaviour of the Earth imply the determination of how temperature varies with depth, and how such temperature variations may have changed throughout geological time. However, studies of this kind are based entirely on measurements made on, or within, a few km of the Earth's surface during the last few decades.

We need to quantify the increase in temperature with depth or *geothermal gradient* relatively near the surface, but below the level at which daily or seasonal variations of temperature are felt (1 m and 20 m, respectively, from the surface).

The most obvious feature of Fig. 5 is that the profile is not a straight line: at a stationary state, where heat flow is constant with depth, the geothermal gradient changes inversely with the thermal conductivity of rocks. Over the depth interval Z_1, the gradient is given by $(T_2-T_1)/Z_1$. Over the depth interval Z_2, the gradient is given by $(T_3-T_2)/Z_2$, and over Z_3 by $(T_4-T_3)/Z_3$.

The average gradient near the surface, say within a few km, is about 0.03°C/m, i.e. 30°C/km, but values as low as about 10°C/km are found in ancient continental crust and very high values (> 100°C/km) are found in areas of active volcanism. Once the gradient

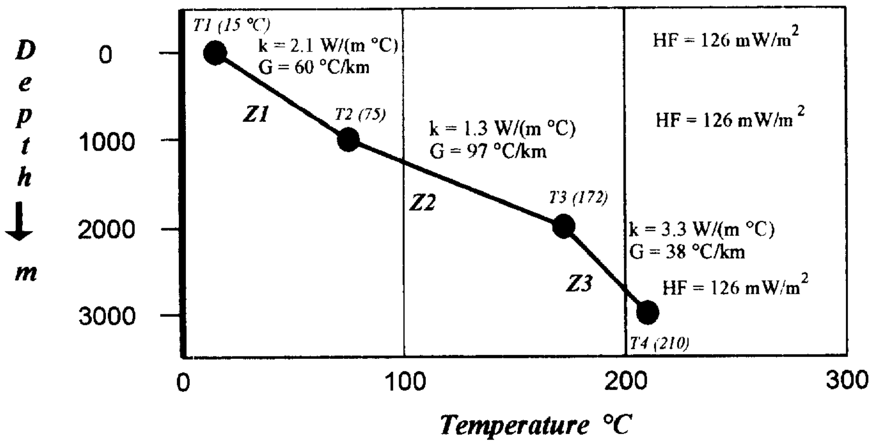

Fig. 5. At a stationary state, where heat flow is constant with depth, the geothermal gradient changes with the thermal conductivity of rocks. *Z1*, *Z2*, *Z3* are depth intervals; *T1*–*T4* are temperatures at the depths shown: *k* is the thermal conductivity of the rocks in the interval: *G* is the geothermal gradient, and HF the heat flow.

has been measured, it can be used to determine the rate at which heat is moving upwards through a particular part of the Earth's crust.

As the heat generally moves upwards through solid impermeable rock, the principal mechanism of heat transfer must be conduction.

The amount of heat flowing by conduction through a unit areas of 1 m^2 of solid rock in a given time, i.e. the rate of heat flow, is proportional to the geothermal gradient $\Delta T/z$ and to a constant of proportionality, k, which is known as the thermal conductivity of rocks:

$Q = \Delta T/z \cdot k$

where Q is the heat flow, ΔT is the temperature difference over the depth interval z (the geothermal gradient), and k, the thermal conductivity of the rock, is defined as the amount of heat conducted per second through an area of 1 m^2, where the temperature gradient is 1 °C/m perpendicular to that area. The unit of thermal conductivity is the W/(m K) (watts per metre per degree kelvin, or per degree centigrade. In both scales of temperature the value of conductivity does not change).

If gradient is expressed in °C/km and conductivity in W/(m °C), heat flow will be in the preferred unit of mW/m^2 (milliwatts per square metre).

GEOTHERMAL FIELDS

Muffler and Cataldi [6] defined *geothermal resources* as "the thermal energy that could reasonably be extracted at costs competitive with other forms of energy at some specified future time".

Geothermal resources are generally confined to areas of the Earth's crust where heat flow higher than in surrounding areas heats the water contained in permeable rocks (reservoirs) at depth. The resources with the highest energy potential are mainly concentrated on the boundaries between plates, where visible geothermal activity frequently exists. By *geo-*

thermal activity we mean hot springs, fumaroles, steam vents, and geysers (Fig. 6). Active volcanoes are also a kind of geothermal activity, on a particularly spectacular large scale.

Geothermal activity in an area is certainly the first significant indication that subsurface rocks in the area are warmer than the norm. The local heat source could be a magma body at 600–900°C, intruded within a few kilometres of the surface. However, geothermal fields can also form in regions unaffected by recent (Quaternary) shallow magmatic intrusions. The anomalous higher heat flow may be due to particular tectonic situations, for example to thinning of the continental crust, which implies the upwelling of the crust–mantle boundary and consequently higher temperatures at shallower depths.

However, we need more than a thermal anomaly to have a productive geothermal resource. We also need a reservoir, which is a sufficiently large body of permeable rocks at a depth accessible by drilling. This body of rock must contain large amounts of fluids, water or steam, which carry the heat to the surface. The reservoir is bounded by cooler rocks hydraulically connected to the hot reservoir by fractures and fissures, which provide channels for rainwater to penetrate underground. These cooler rocks crop out at the surface where they represent the so-called *recharge areas* of the geothermal reservoir. Thermal waters or steam are, in fact, mainly rainwater that infiltrates into the recharge areas at the surface and proceeds to depth, increasing in temperature while penetrating the hot rocks of the reservoir.

Water moves inside the reservoir by convection, due to density variations caused by temperature, transferring heat from the lowest parts of the reservoir to its upper parts [7]. The result of the convection process is that the temperature in the upper parts of the reservoir is not much lower than the temperature of its deeper parts, so that the lowest

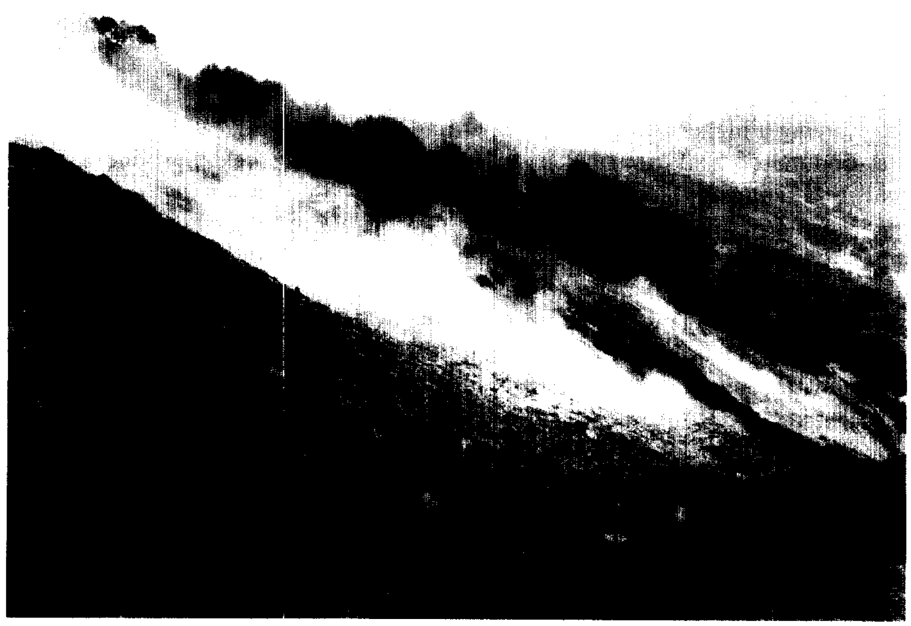

Fig. 6. Geothermal manifestations, fumaroles, at Larderello geothermal steamfield, Tuscany, Italy.

values of the geothermal gradient are actually found inside the reservoir. Convection, implying a real transfer of matter, is therefore a more efficient process of heat transfer than conduction, the other mechanism of heat transfer typical of less-permeable rocks. Heat is transferred by conduction from the magma body towards the permeable reservoir rocks, the reservoir, filled with fluids.

Hot fluids often escape from the reservoir and reach the surface, producing the visible geothermal activity described above.

The heat source, the reservoir, the recharge area, and the connecting paths through which cool superficial water penetrates the reservoir and, in most cases, escapes back to the surface, compose the *hydrothermal system* [8].

The reservoir is the most important part of the system, from the point of view of energy utilisation, and in fact we define the reservoir as "the hot part of the geothermal system that can be exploited either by extracting the fluid contained (water, steam, or various gases), or using anyhow its heat" [9]. Existence of a hydrothermal system will not necessarily ensure production at industrial levels. Only a part of its rocks may be permeable, constituting a fluid reservoir, so that the system will be able to produce industrially from that part only. This part is called a *geothermal field*, and the geographic name of the locality usually gives its name to the field (for example, The Geysers geothermal field in California, Tiwi field in the Philippines, Wairakei field in New Zealand, Larderello field in Italy).

Four types of geothermal systems have been identified: hydrothermal, hot dry rock, geopressured, and magmatic. The systems exploited at present are the hydrothermal systems. The other three may be exploited industrially in the future after more technological development.

Hydrothermal systems

Hydrothermal systems have reservoirs that produce water either in liquid phase or as steam (wet or dry). These reservoirs (or fields) are traditionally classified as

- water-dominated, or
- vapour-dominated,

the latter having a higher energy content per unit fluid mass.

Water-dominated fields are further divided into hot water fields, producing hot water, and fields producing mixtures of water and steam, called wet steam fields.

Water-dominated fields. Hot water fields are capable of producing hot water at the surface at temperatures up to 100°C. They are the geothermal fields with the lowest temperature, and the reservoir contains water in liquid phase. The reservoir may not have a cover of impermeable rock acting as a lid; however, some of these thermal aquifers are overlaid by confining layers that keep the hot water under pressure. Temperatures in the reservoir remain below the boiling point of water at any pressure because the heat source is not large enough. The surface temperature is not higher than the boiling temperature of water at atmospheric pressure.

These fields may also occur in areas with normal heat flow. On the surface there are often thermal springs whose temperatures are, in some cases, near the boiling point of water. A hot water field is of economic interest if the reservoir is found at a depth of less than 2 km, if the salt content of the water is lower than 60 g/kg, and if the wells have high flow-rates (above 150 t/h). The best-known examples of exploited hot water fields are those of the Pannonian basin (Hungary), the Paris basin, (France), the Aquitanian basin (France), many

Russian fields, the Po river valley (Italy), Klamath Falls (Oregon, U.S.A.), and Tianjin (China).

Wet steam fields contain pressurised water at temperatures exceeding 100°C and small quantities of steam in the shallower, lower pressure parts of the reservoir. The dominant phase in the reservoir is the liquid one, and it is this phase that controls the pressure inside the reservoir. Steam is not uniformly present, occurring in the form of bubbles surrounded by liquid water, and does not noticeably affect fluid pressure.

An impermeable cap rock generally exists to prevent the fluid from escaping to the surface, thus keeping it under pressure. This is common, but not absolutely necessary. In fact, at any depth below the water table water bears its own hydrostatic pressure. When the fluid is brought to the surface and its pressure decreases, a fraction of fluid is flashed into steam, while the greater part remains as boiling water (Fig. 7). Once a well penetrates a reservoir of this type, the pressurised water rises into the well because pressure is lower there. The consequence of the pressure drop is the vaporisation of part of the water, with the result that the well eventually produces hot water and steam, with water as the predominant phase. The water–steam ratio varies from field to field, and even from one well to the next within the same field. As in many cases only steam is used to produce electrical energy, liquid water must be removed at the surface in special separators.

The surface manifestations of these fields include boiling springs and geysers. The heat source is large and generally of magmatic origin. The water produced often contains large quantities of chemicals (from 1 to over 100 g/kg of fluid, in some fields up to 350 g/kg). These chemicals may cause severe scaling problems to pipelines and plants. They are mainly chlorides, bicarbonates, sulphates, borates, fluorides, and silica.

More than 90% of the hydrothermal reservoirs exploited on an industrial scale are of the wet steam type. Electricity generation is their optimal utilisation. One important economic aspect of wet steam fields is the large quantity of water extracted with the steam (for example 6600 t/h at Cerro Prieto, Mexico). Owing to its generally high chemical content, this water has to be disposed of through reinjection wells drilled at the margins of the reservoir.

Examples of wet steam fields producing electricity, are: Cerro Prieto, Los Azufres and Los Humeros (Mexico), Momotombo (Nicaragua), Ahuachapán-Chipilapa (El Salvador), Miravalles (Costa Rica), Zunil (Guatemala), Wairakei, Ohaaki and Kawerau (New Zealand), Salton Sea, Coso and Casa Diablo (California), Puna (Hawaii), Soda Lake, Steamboat and Brady Hot Springs (Nevada), Cove Fort (Utah), Dieng and Salak (Indonesia), Mak-Ban, Tiwi, Tongonan, Palinpinon and Bac Man (Philippines), Pauzhetskaya and Mutnovsky (Russia), Fang (Thailand), Kakkonda, Hatchobaru and Mori (Japan), Olkaria (Kenya), Krafla (Iceland), Azores (Portugal), Kizildere (Turkey), Latera (Italy), and Milos (Greece) (Fig. 3).

Vapour-dominated fields. Vapour-dominated reservoirs (fields) produce dry saturated, or slightly superheated steam at pressures above atmospheric. They are geologically similar to wet steam fields, but the heat transfer from depth is certainly much higher. Research suggests that their permeability is lower than in wet steam fields, and the presence of the cap rock is of fundamental importance here. Water and steam coexist, but steam is the continuous predominant phase, regulating the pressure in the reservoir: the pressure is practically constant throughout the reservoir. These fields are called dry or superheated fields. Produced steam is in fact generally superheated, with small quantities of other gases, mainly CO_2 and H_2S (Fig. 8).

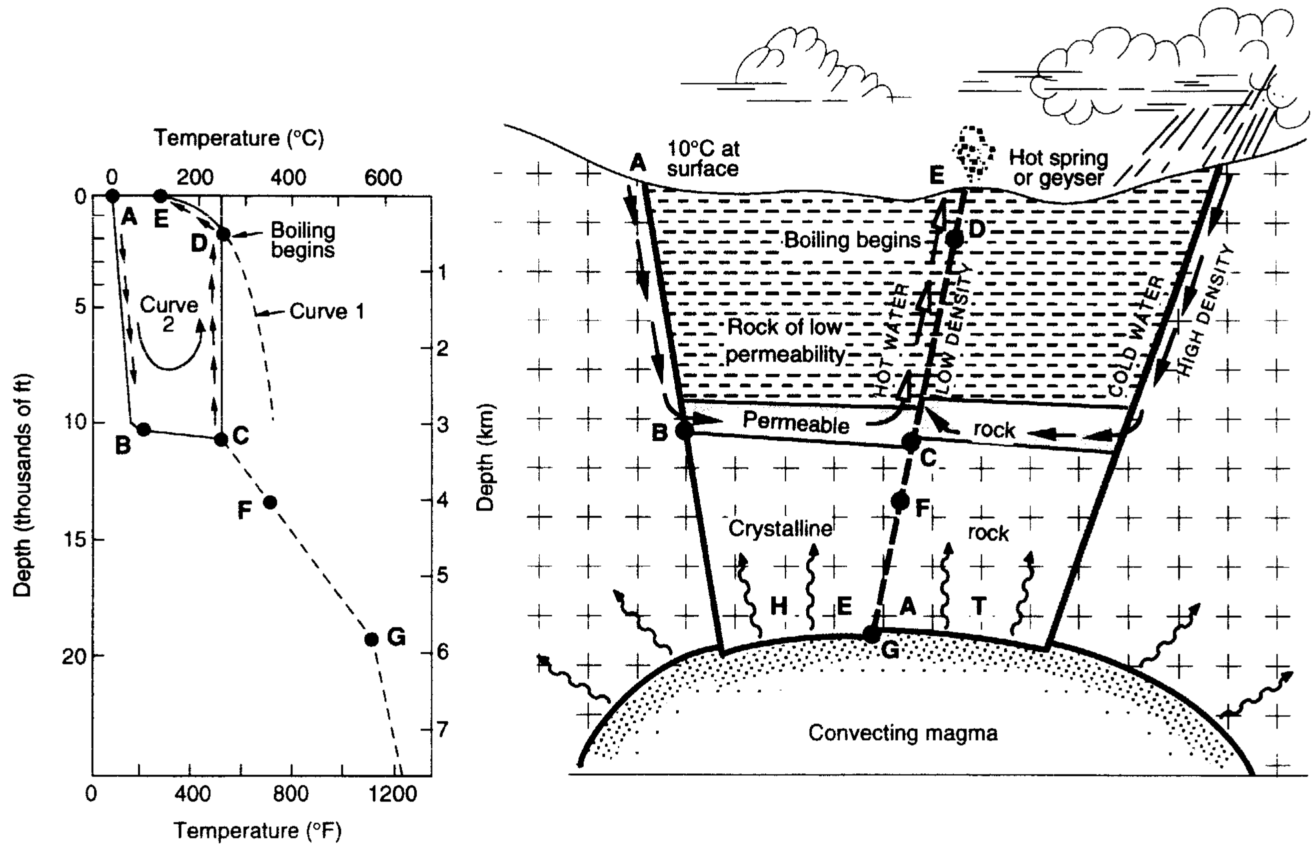

Fig. 7. Model of a wet steam field. Curve 1 is the reference curve for the boiling point of pure water. Curve 2 shows the geothermal gradient along a typical circulation route from recharge at point A to discharge at E. (From Ref. [10].)

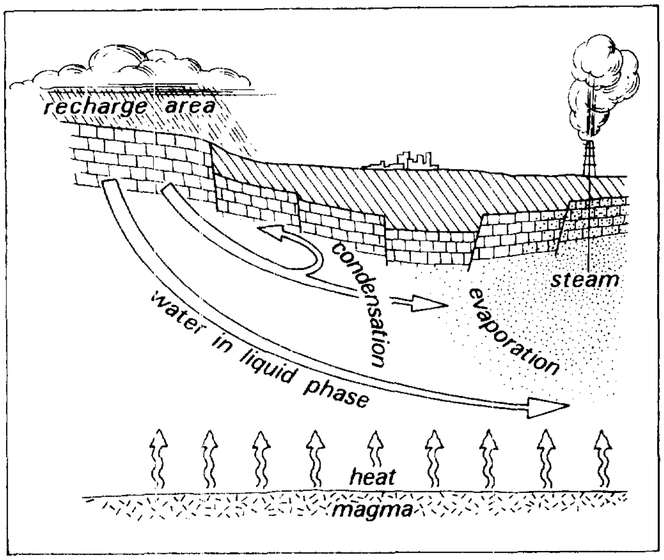

Fig. 8. Model of a vapour-dominated field producing dry or superheated steam. Steam is the continuous predominant phase in the reservoir. Pressure is approximately constant throughout the reservoir.

The mechanism governing production in these fields is believed to be the following. When a well penetrates the reservoir and production begins, a depressurised zone forms at the well-bottom. This pressure drop produces boiling and vaporisation of the liquid water in the surrounding rock mass. A dry area, i.e. without liquid water, forms near the well-bottom and steam flows through this zone. Steam crossing the dry area starts to expand and cool, but the addition of heat from the very hot surrounding rocks keeps the steam temperature above the vaporisation value for the pressure existing at that point. As a result, the well produces superheated steam with a degree of superheating which may reach 100°C, for example with well-head pressures of 5–10 bars and a steam outlet temperature of more than 200°C.

D'Amore and Truesdell [11] proposed a model of the evolution of a vapour-dominated field. The model is based on changes with time in the chemistry of steam produced by the wells. These authors believe that during production steam originates from progressively deeper sources. At the very beginning of exploitation the main steam source is the liquid water present in a so-called zone of condensation located in the upper part of the reservoir, immediately below the impermeable cover. As fluid extraction proceeds, this zone tends to become unproductive, and steam from a lower zone containing biphase fluid (water and steam) migrates towards the wells. Finally, if production continues, steam originating from a much deeper boiling liquid brine will start to enter the well.

Ingebritsen and Sorey [12] confirmed with their mathematical model that these reservoirs have low rates of fluid throughflow and extensive zones dominated by steam at pressures near vapourstatic, i.e. much lower than hydrostatic due to the very low specific gravity of steam. Low-permeability rocks surround these reservoirs and act as barriers which bound the vapour-dominated zones.

Surface geothermal activity associated with vapour-dominated fields, whether dry or

superheated, is similar to the activity present in wet steam fields. About half of the geothermal electric energy generated in the world comes from six vapour-dominated fields: Larderello (Italy) (Fig. 9), Mt. Amiata (Italy), The Geysers (California) (Fig. 10), Matsukawa (Japan) (Fig. 11), Kamojang and Darajat (Indonesia).

Of the approximately 100 hydrothermal systems that have been investigated, less than 10% are vapour-dominated, 60% are wet steam fields (water dominated), and 30% produce hot water [8].

Summarising, it is worth emphasising that a geothermal well can produce:

- *Hot water.*
- *Wet steam*, where steam coexists with its generating liquid (water). This is a biphase (or two-phase) system.
- *Dry steam*, where the steam does not contain water in suspension. This is a limit state, to superheated steam. Wet and dry steam are both called *saturated* steam. The temperature of the steam corresponds to the temperature of vaporisation (or of saturation) at that pressure. [For example, at a pressure of 1 bar (0.1 MPa), the vaporisation or saturation or boiling temperature of water is 100°C, whereas at 10 bar, (1 MPa), the vaporisation temperature is 180°C].
- *Superheated steam*, where the temperature of the steam is higher than the corresponding temperature of vaporisation at that pressure.

The *quality* of steam (or dryness factor, or steam fraction) is the weight percentage of steam in the liquid–steam mixture. It may vary between 0% (liquid) and 100% (dry steam).

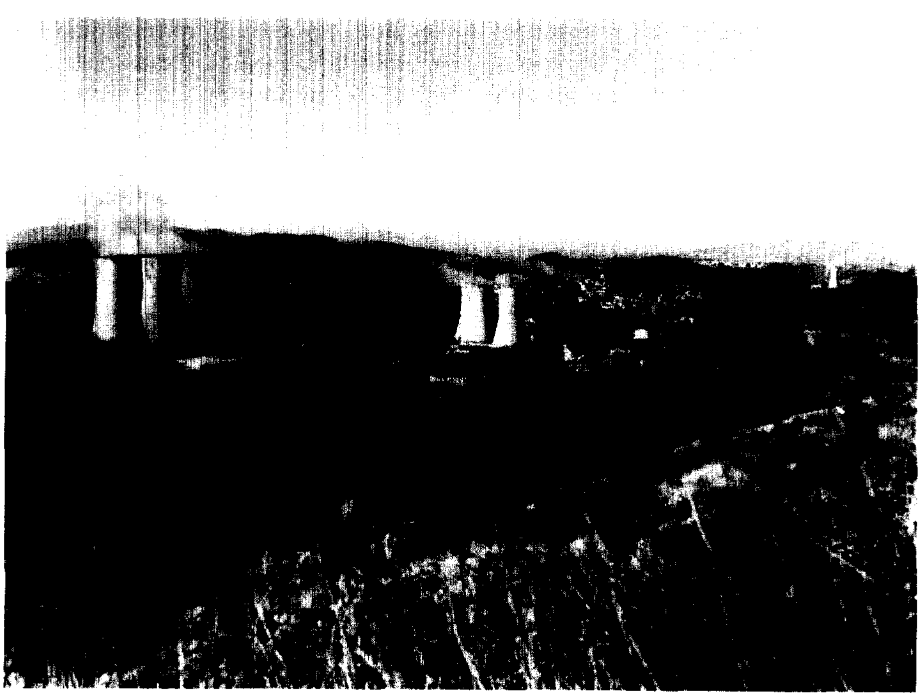

Fig. 9. Larderello geothermal steam field, Tuscany, Italy. The installed geothermal electric capacity of the field was 461 MW_e in December 1994 [13].

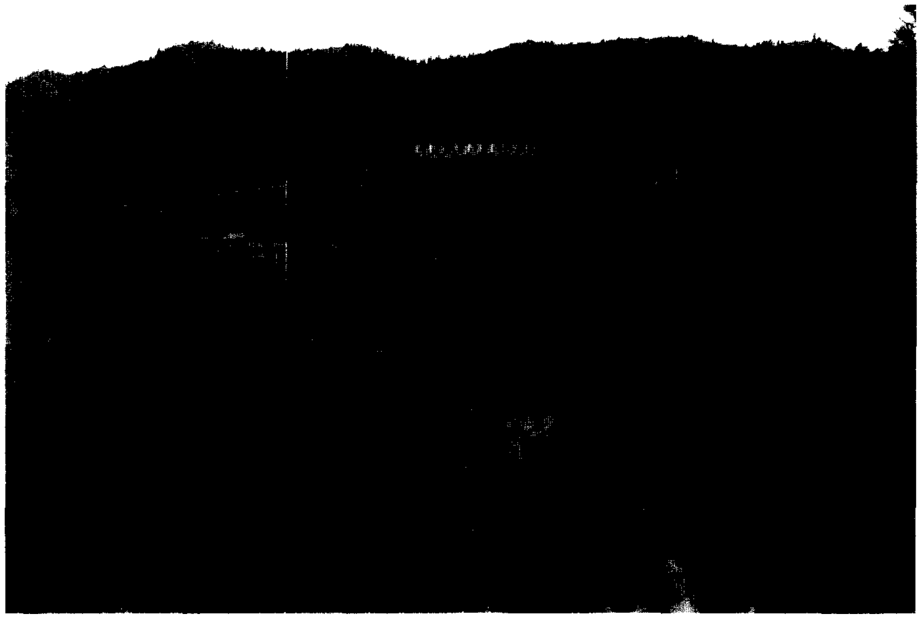

Fig. 10. A power plant at The Geysers geothermal steam field, California. The field generation capability fell to 1193 MW_e in 1993 [14].

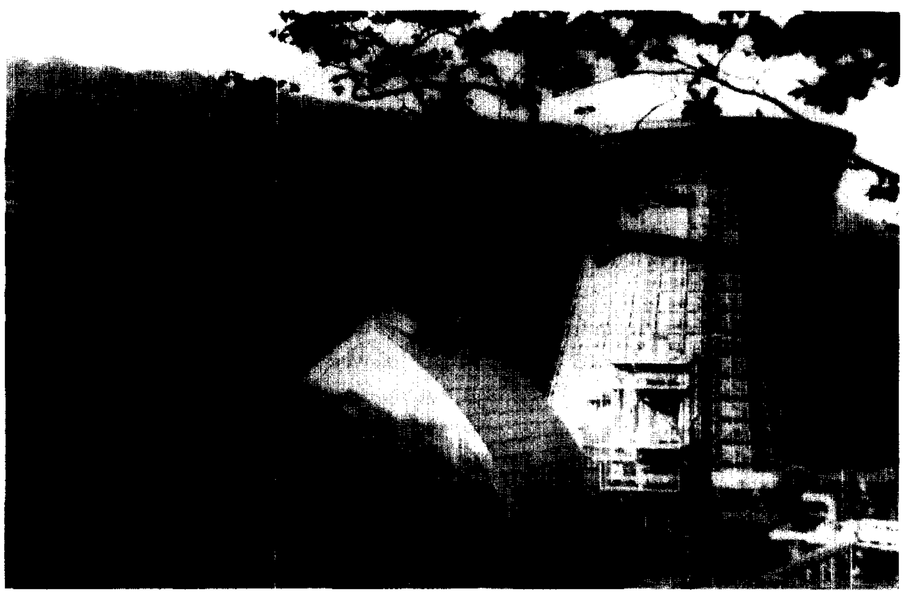

Fig. 11. Matsukawa geothermal power plant, the oldest plant in Japan, 23.5 MW_e [14].

The *enthalpy* of water or of steam is the heat content per unit mass, in kcal/kg or in kJ/kg (1 kcal/kg = 4.18 kJ/kg).

The production of steam and water from a geothermal reservoir can be illustrated on a pressure–enthalpy diagram for pure water, as shown in Fig. 12. The solid line is the

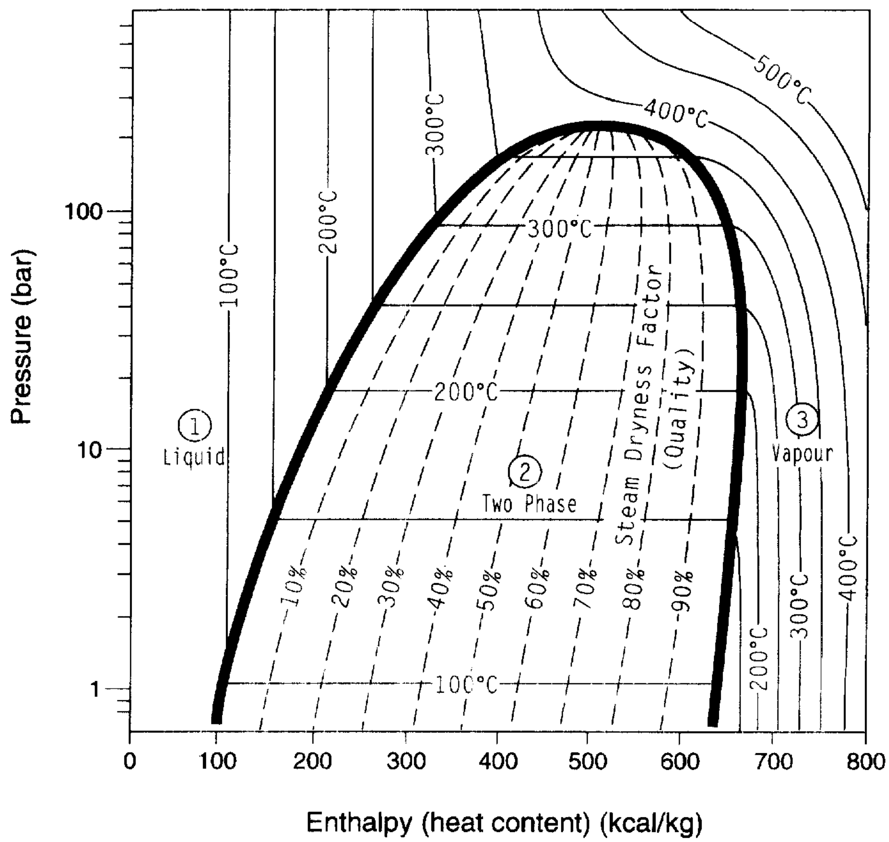

Fig. 12. Pressure versus enthalpy diagram for pure water and steam, with thermodynamic fluid reservoir conditions. (1) Liquid water, (2) two-phase liquid : steam and water ; (3) superheated steam. (From Ref. [15], modified.)

vaporisation or saturation curve for liquid water. If we consider a steam–water mixture on the saturation curve at 250°C and 40 bar (4 MPa), wells at this thermodynamic state can produce fluid in a variety of ways. For example, production could be saturated liquid at an enthalpy of 260 kcal/kg (1086 kJ/kg), or saturated (dry) steam at an enthalpy of 670 kcal/kg (2800 kJ/kg), or any mixture of steam and liquid water with an enthalpy, and quality, ranging between that of dry steam and water.

The average steam composition of some geothermal fields under exploitation is given in Table 1. Geothermal steam often contains gases such as CO_2, H_2S, HCl, HF, NH_3, CH_4, and H_2, in a range that varies from field to field. In a particular field the content of these gases tends to decrease with time as a result of production.

Reservoir temperatures and enthalpies of steam in geothermal fields presently generating electricity vary within a wide range, as shown in Table 2, compiled by Sommaruga and Zan [20].

Shut-in pressures measured at the well-head always decline with time as a consequence of fluid extraction and depletion of the reservoir. Geothermal energy has often been said to be a renewable energy resource. However, on the timescale normally used in human

Table 1. Composition of steam from some geothermal fields

Constituents (g/kg)	The Geysers U.S.A.[1]	Larderello Italy[2]	Matsukawa Japan[3]	Wairakei New Zealand[4]	Cerro Prieto Mexico[5]
H_2O	995.9	953.2	986.3	997.5	984.3
CO_2	3.3	45.2	12.4	2.3	14.1
H_2S	0.2	0.8	1.2	0.1	1.5
NH_3	0.2	0.2			0.1
CH_4+H_2	0.2	0.3			
Others	0.2	0.3	0.1	0.1	

[1] Ref. [16]; [2] Ref. [17]; [3] Ref. [18]; [4] Ref. [19]; [5] Ref. [16].

Table 2. Reservoir temperature and enthalpies of geothermal fields generating electricity (From Ref. [20])

Geothermal fields	Reservoir temp. °C ( ) max temp.	Enthalpy max kcal/kg (kJ/kg)
Vapour-dominated systems		
The Geysers (U.S.A.)	237 (310)	718 (3000)
Larderello (Italy)	200 (420)	742 (3100)
Amiata (Italy)	154 (344)	622 (2600)
Matsukawa (Japan)	220	
Kamojang (Indonesia)	175 (248)	665 (2780)
Water-dominated systems		
Wairakei (New Zealand)	230 (290)	281 (1175)
Broadlands (New Zealand)	280 (326)	401 (1675)
Imperial Valley fields (U.S.A.)	160 (370)	239 (1000)
Cerro Prieto (Mexico)	265 (388)	581 (2430)
Los Azufres (Mexico)	175 (300)	646 (2700)
Los Humeros (Mexico)	310 (418)	622 (2600)
Momotombo (Nicaragua)	210 (327)	646 (2700)
Ahuachapan (El Salvador)	210 (240)	660 (2760)
Tiwi (Philippines)	273 (309)	670 (2800)
Mac-Ban (Philippines)	207 (313)	428 (1790)
Hatchobaru (Japan)	218 (308)	538 (2250)
Olkaria (Kenya)	205 (330)	574 (2400)
Krafla (Iceland)	205 (344)	641 (2680)

society, geothermal resources are not, strictly speaking, renewable. They are renewable only if the heat extraction rate does not exceed the reservoir replenishment rate. Exploitation through wells, sometimes using downhole pumps in the case of non-electrical uses, leads to the extraction of very large quantities of fluid, and consequently to a reduction or depletion of the geothermal resource in place.

Disposal of the spent cooled fluid after use is also an important operation in each geothermal application. In electrical uses, steam condenses into a water that is often rich in salts, and this polluting waste must be disposed of accordingly. More than 95% of the fluid produced is often reinjected into the reservoir as water, helping to limit pressure losses

and to replace at least part of the fluid extracted. Models provide invaluable help in the selection of reinjection areas, the depth of reinjection, and the optimal fluid reinjection rate.

The key to a successful geothermal project is to ensure, by careful reservoir evaluation and monitoring, that the geothermal reservoir will last for the lifetime of the geothermal installations [21]. Experience has taught us that good reservoir management practices can assure an adequate steam supply for many decades.

The origin of steam

The first scientifically sound hypothesis on the origin of geothermal fields was advanced by the Italian geologist Bernardino Lotti at the beginning of this century. At that time, Larderello geothermal field in Tuscany, Italy, was the only field to have been studied geologically, due to the industrial extraction of the boric acid from the thermal springs and natural steam issuing from shallow wells in the area. Lotti attempted to explain the origin of the vast quantities of boric acid in the hot fluids of this part of Tuscany. It was already known at that time that granite magma can contain water, which is released during the cooling of the magma and its crystallisation process, both occurring at depth. Lotti concluded that the boron-rich steam and water at Larderello originated from a deep magmatic intrusion, and that steam reached the surface through faults and fissures connected with the magmatic body, thus acting as channels for the fluids to flow to the surface. Geothermal steam was, according to Lotti's hypothesis, of magmatic origin.

Lotti's hypothesis remained the only geological explanation for the origin of steam for more than half a century until the French geologist Jean Goguel, in a paper published in 1953 on the thermal regime of underground waters [22], presented his views on this issue, which overturned the previous concepts on a thermodynamic basis. Goguel showed analytically that a granite body undergoing cooling at depth can heat rainwater contained in overlying rock to boiling point, and that the main origin of steam is rainwater that percolates into the reservoir from the surface. A small percentage ($< 10\%$) of the steam could, however, still be of magmatic origin.

Goguel's theory on the meteoric origin of steam and hot water was confirmed independently in 1956 by the geochemists H. Craig, G. Boato and D. E. White [23], who studied the isotopic composition of the ratios hydrogen/deuterium and oxygen-16/oxygen-18 of the thermal waters and the rainwater of the same localities*.

Linking the origin of geothermal steam to rainwater rather than to magma, was to have an important effect on the exploration and development of a geothermal field, by radically changing the exploration targets. The wells were no longer targeted at the steam conduits (faults and fractures) carrying the steam from magma to the shallower rocks (Fig. 13), but were concentrated on areas that showed evidence of the existence of a deep geothermal reservoir with an adequate volume of permeable rock able to contain hot fluids, and of the

* When writing the history of geothermal energy, nobody has so far mentioned a curiosity. The meteoric origin of the water of thermal springs and steam vents has been clearly hypothesised more than three centuries ago, without of course any scientific proof. The Jesuit Father Athanasius Kircher, distinguished naturalist, in his book *Mundus Subterraneus* (The Underground World) published in Amsterdam in 1678 and enriched with beautiful drawings, maintained that if the fire within the bowels of the Earth (i.e. the magma) passes near underground caverns filled with water, when this water is heated or vapourised and comes to the surface, it will emerge in the form of hot springs or fumaroles [25].

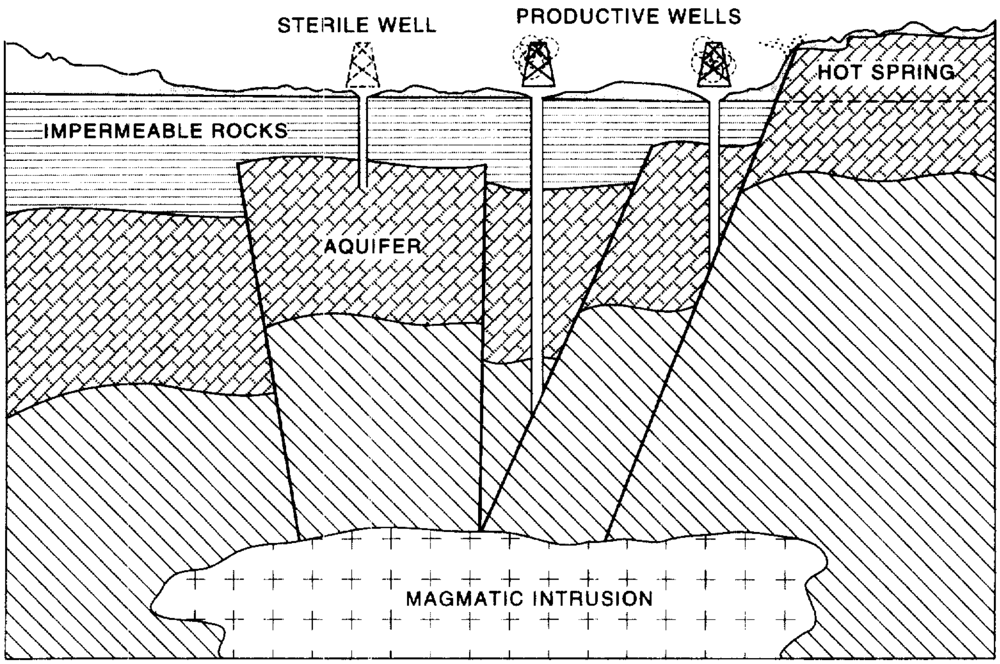

Fig. 13. The first hypothesis on the origin of geothermal steam, by the Italian geologist B. Lotti, made at the beginning of this century. Steam originated from a deep magma intrusion (juvenile steam), and productive wells were thought to be only those crossing steam conduits (faults) reaching the magma intrusion. (From Ref. [24].)

presence of a heat source and a fluid recharge area at the surface, feeding the reservoir at depth. Another, no less significant consequence concerned the exploitation of a geothermal field. When steam was thought to be of magmatic origin, little thought was given to the hydrogeological conditions of the field, as the water contained in a granite magma was supposed to be able to sustain production for a long time. A meteoric origin, on the other hand, entails some considerations of the hydraulic and thermal balance of the field, as the hot water and steam produced by the wells must be replaced, at least partially, by rainwater. This water infiltrates to depths in areas that may be far from the field, and has to be heated by the hot rocks though which it moves. The consequence of this new understanding of the origin of steam is the currently accepted view that geothermal energy is not entirely a renewable energy source, as experience has shown that fluids are generally extracted at a faster rate than they are replaced in the reservoir.

THE GEOLOGIC ENVIRONMENT OF GEOTHERMAL ENERGY

It is widely accepted that most geothermal fields are localised in areas of young tectonism and volcanism (Cenozoic, 65 million years ago), primarily along active plate boundaries (Fig. 3).

Diverging boundaries between plates are zones in which new crust is created by extensive igneous intrusion and extrusion and, accordingly, they are favourable sites for the presence of geothermal fields. Examples of mid-oceanic spreading ridges above sea level, and associ-

ated geothermal fields, are Iceland, the Azores islands, and the Afar depression in Ethiopia. There are also spreading ridges on continents: the East Pacific Rise, with the geothermal fields of Cerro Prieto (Mexico) and Imperial Valley (U.S.A.), and the East African Rift, with the fields of Langano (Ethiopia) and Olkaria (Kenya).

Converging plate boundaries are those belts along which two plates move towards each other, resulting in the consumption of lithosphere by the thrusting of one plate beneath the other (the process called *subduction*). Melting of downthrust crust produces pods of magma that rise into the upper plate and act as heat sources for overlying geothermal reservoirs. Geothermal fields clearly related to subduction zones where oceanic plates bend downwards beneath a continental plate are those of Japan (near the contact between the Pacific plate and the Eurasian plate), Indonesia (Indian–Australian and Eurasian plates), New Zealand (Pacific and Indian–Australian plates), Chile and Central America (Nazca and South American plates) and, if their existence is proved, the fields in the Cascade Mountains in the western United States and on the island arcs of the Aleutian islands of Alaska.

Converging continental plates, where a collision takes place between continents, as in the case of the northwest part of the Indian–Australian and the Eurasian plates, produce conditions that are also favourable for the formation of geothermal fields. Examples are the Indian and Chinese Himalayan geothermal fields.

In the Mediterranean area, where the Eurasian and African continental plates collide, the crust is young and also shows the effects of the subduction of the African beneath the Eurasian plate. This is, in fact, the area of the Eolian and Hellenic trenches, the Tyrrhenian, Algerian–Provençal and Aegean marginal basins, and a system of tensional horsts and grabens (Tuscany, Latium and Campania, and Italy) with associated active and recent volcanism. One important result of the rather irregular distribution of these geothermal areas is that the majority of Mediterranean countries are restricted to low-temperature (< 100 C) geothermal fields, and thus to non-electrical uses of heat, whereas the high-temperature sources eligible for electricity generation are confined to central and southwest Italy, eastern Greece and west Turkey.

Intraplate melting anomalies are responsible for Quaternary volcanism (less than 2 million years old) and associated geothermal fields where mantle plumes rise beneath a continent (Yellowstone in the continental U.S.A.) or an oceanic plate (Hawaii). Rather than breaking up the plate, the plume act as a heat source (or hot spot) beneath the moving plate. As the plate moves over the plume, a line of volcanoes forms. The volcanoes are gradually carried away from the eruptive centre, sinking as they go because of cooling.

EXPLORATION FOR GEOTHERMAL ENERGY

Present technology and economic factors restrict extraction of geothermal energy to the upper few kilometres of the Earth's crust. Geothermal wells, to date, are drilled to less than 5 km depth.

As in the search for any natural resource, a strategy for geothermal energy exploration must be defined and followed. Once a geothermal region has been identified, the next step is to use various exploration techniques to locate the most interesting geothermal areas and identify suitable targets for fluid production.

It is necessary to estimate temperature, reservoir volume and permeability at depth, as well as to predict whether wells will produce steam or just hot water. Ideally we should also

estimate the chemical composition of the fluid to be produced. To obtain this varied information, there are a number of exploration techniques available:

- inventory and survey of surface manifestations,
- hydrogeological surveys,
- geochemical surveys,
- geophysical surveys,
- exploratory wells.

Because of the high cost of exploration, it is normally approached in a prescribed sequence of steps, altering the order from time to time depending on the prior knowledge of the area in question. In some cases, high costs will lead to the elimination of some steps in the sequence.

Inventory and survey of surface manifestations

A knowledge of surface thermal manifestations (hot springs, steam vents, fumaroles, etc.) and their physical and chemical characteristics is of fundamental importance (Fig. 14). This information, which can usually be obtained simply and at relatively low cost, is extremely useful for subsequent planning of exploration.

The surface survey is conducted in two consecutive phases: (1) the collation, processing and standardisation of published and recorded data relative to local manifestations (chemistry, temperature, flow-rates, etc.), and (2) the collection of new data, water samples, gas samples, temperature measurements, etc.

Hydrogeological surveys

There are not limited to studies of groundwaters, but also include geological surveys that provide information on the stratigraphic and structural framework of the area. Hydro-

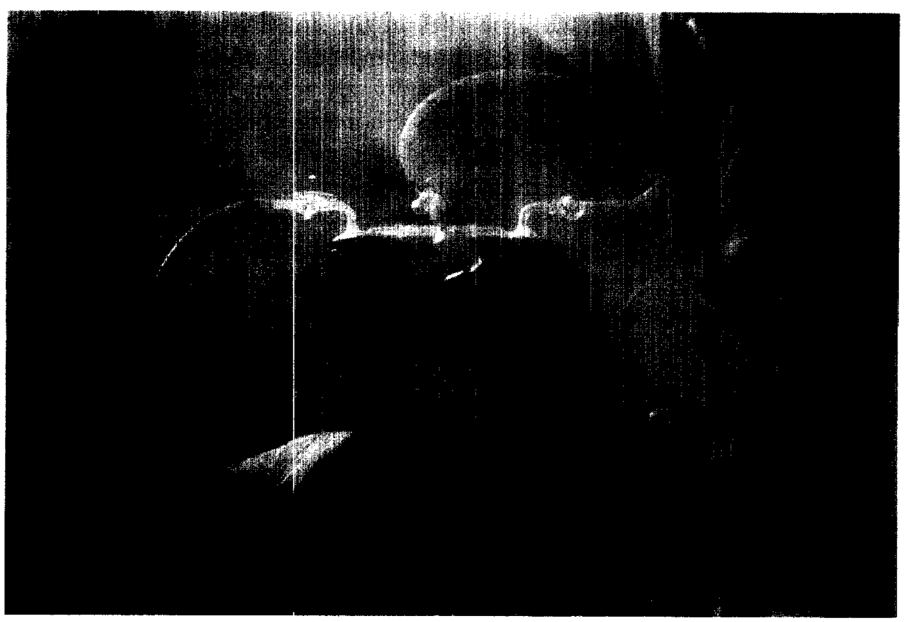

Fig. 14. Sampling of geothermal gases.

geological surveys permit us to correlate the hydrothermal manifestations with faults, fractures, and other tectonic features. These surveys are aimed at identifying the distribution of confined and unconfined aquifers* that will permit us to reconstruct the underground pattern of water circulation. Mathematical models have proved to be of great help in hydrogeological surveys.

Geochemical surveys

Geochemical exploration can start simultaneously with geologic and hydrogeologic reconnaissance, provided that springs and other geothermal manifestations are available for fluid sampling (Fig. 14).

With geochemical techniques we can estimate the temperature of deep reservoirs by analysing hot spring samples and calculating the ratios of certain chemical elements (i.e. Na, K, Mg, Ca, etc.), and making some adjustment for the degree of mixing of the hot geothermal reservoir water with cooler groundwater in the shallow part of the hydrothermal system. The amount of dissolved silica in the sampled waters is also an indicator of the reservoir temperature based on the temperature-dependent solubility of quartz and other silica minerals [26].

Hydrogen and oxygen isotopes can be used to identify the recharge areas of the geothermal reservoirs, while the content of tritium and ^{14}C radioisotopes† permit us to evaluate the age of the geothermal fluids, i.e. the time lapsed since their infiltration into the ground. Geochemical surveys can also offer information on the direction of movement of subsurface groundwaters and the type of corrosion and scaling problems that could be encountered during the operation of wells and a plant.

Geophysical surveys

Classical geophysical techniques, namely seismic, gravity, and magnetic surveys as applied to geothermal research, can be defined as indirect methods. These methods, in fact, are not directly associated with the properties of the hot fluids that are being sought. Rather, they yield information about the attitude and nature of the host rocks. However, there are other geophysical methods that may directly reveal variations in the physical properties of the rocks caused by the presence of hot and saline fluids. These techniques include electrical-resistivity, electromagnetic, and thermal-measurement methods.

Seismic methods. Elastic waves are transmitted through rocks, and their velocities can be used to help determine the structure and properties of rock bodies. Seismic waves are introduced into the Earth by detonating an explosive charge in a shallow borehole or by using a large mass to thump the surface. Returns of seismic waves are measured at the surface. Seismic waves also originate naturally from earthquakes and microearthquakes, and these waves can also be detected at the surface. Interpretation of the seismic information can provide data on the location of active faults that can channel hot fluids towards the surface (Fig. 15).

Gravity methods. Variations in the Earth's gravity field are caused by changes in the density of subsurface rocks. Gravity surveys are rather simple and inexpensive (Fig. 16).

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* A confined aquifer is an aquifer bounded above and below by rock beds of distinctly lower permeability than that of the aquifer itself.

† A radioisotope is a radioactive isotope of a chemical element.

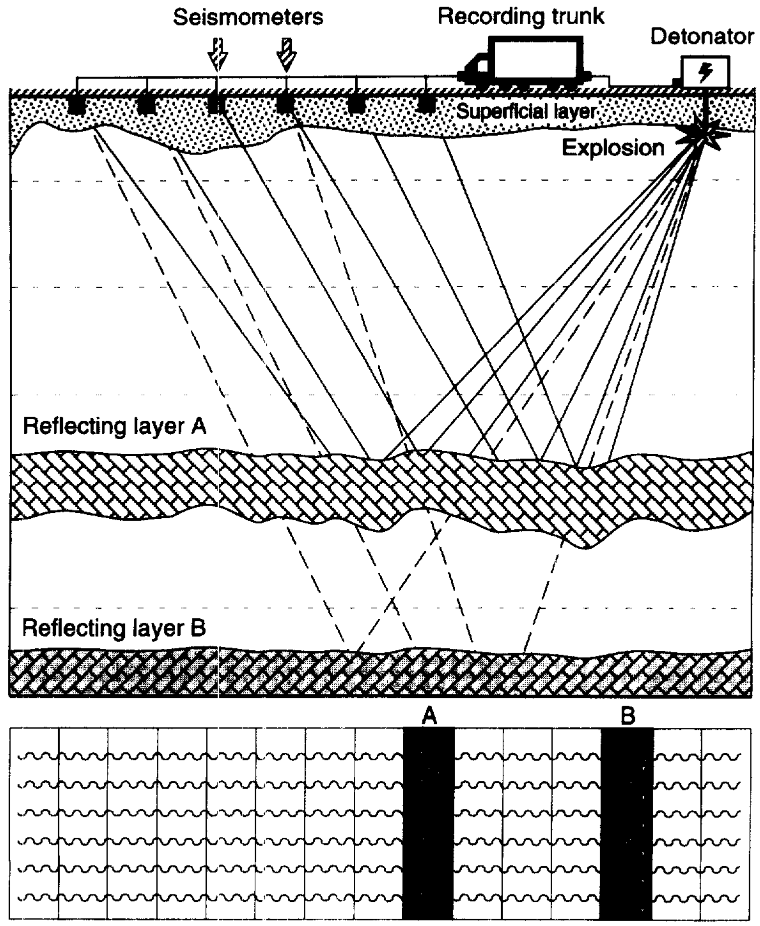

Fig. 15. An active seismic survey. Solid lines show the reflected elastic waves, dashed lines show the refracted waves penetrated at greater depth. At bottom the seismogram showing the recorded vibrations versus time.

Gravity anomalies alone are not necessarily indicative of a geothermal region, but they do give valuable information on the type of rocks at depth and their distribution and geometric characteristics.

Magnetic surveys. The Earth has a primary magnetic field which induces a magnetic response in certain minerals at and near the Earth's surface. By detecting spatial changes of the magnetic field, the variations in distribution of magnetic minerals may be deduced and related to geologic structure. However, each magnetic mineral has a Curie temperature, above which it loses its magnetic properties. For iron, the Curie temperature is less than 800°C [27]. The usefulness of magnetic surveys in geothermal exploration is controversial.

Electrical-resistivity surveys. Most electrical geophysical methods are based on measurement of the electrical resistivity of the subsurface. Resistivity in the Earth is often largely affected by electrical conduction within waters occupying the pore spaces in the rock. Consequently, resistivity varies considerably with porosity. Temperature and salinity of interstitial fluids tend to be higher in geothermal reservoirs than in the surrounding rocks.

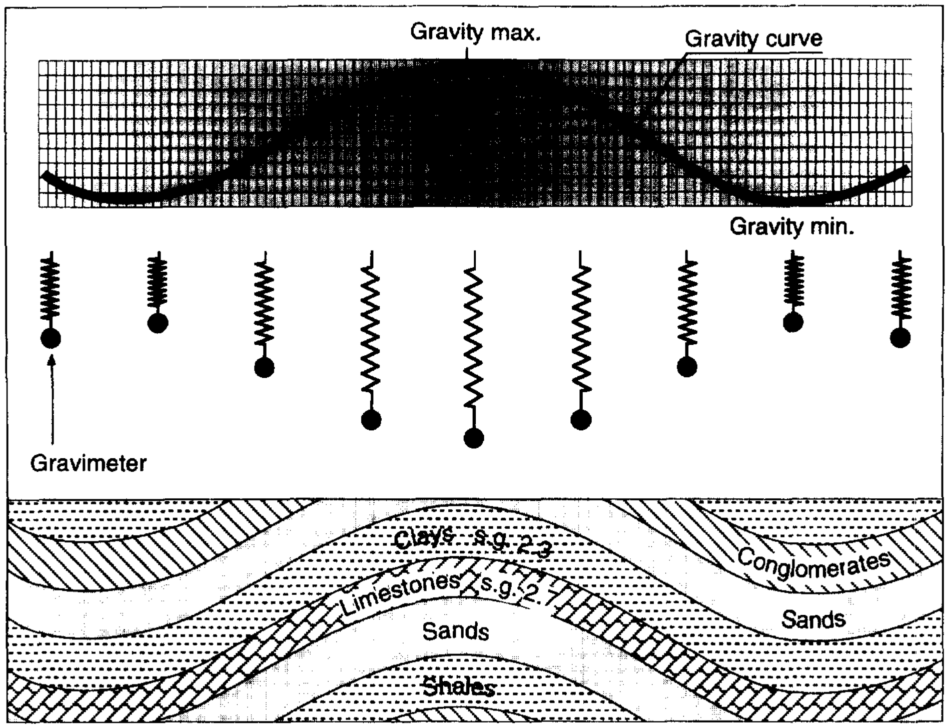

Fig. 16. A gravity survey. Schematic relationship between rock structure and vertical gravitational pull, based on the assumption that the deeper rock horizons are denser than the shallower ones; s.g is the specific gravity of the rock.

Consequently, the resistivity of geothermal reservoirs is generally relatively low. It is this contrast in resistivity between hot water-saturated rocks and the surrounding colder rocks that is used in resistivity surveys. These techniques are based on injection of current into the ground and measurement of voltage differences produced as a consequence at the ground surface (Fig. 17).

Electromagnetic surveys. Induction or electromagnetic methods are a tool for determining the electrical resistivity distribution in the Earth by means of surface measurements of transient electric and magnetic fields. These fields can be naturally or artificially generated. These methods are more suitable for measuring the low resistivities of geothermal reservoirs than the above-mentioned electrical-resistivity methods. Furthermore, in geothermal areas the surface resistivity is sometimes so high as to prevent current from entering the ground, and the electromagnetic methods, with a much deeper penetration, help eliminate the screening effect of very resistive surface rocks.

Thermal-measurement surveys. In geothermal research the traditional geophysical methods mentioned above, which originally had been developed for the oil industry, are used side by side with more specific techniques. Geothermal prospecting provides information on the thermal conditions of the subsurface, the areal distribution of the Earth's heat flow, and the location and intensity of thermal anomalies. To be more specific, geothermal prospecting allows us to:

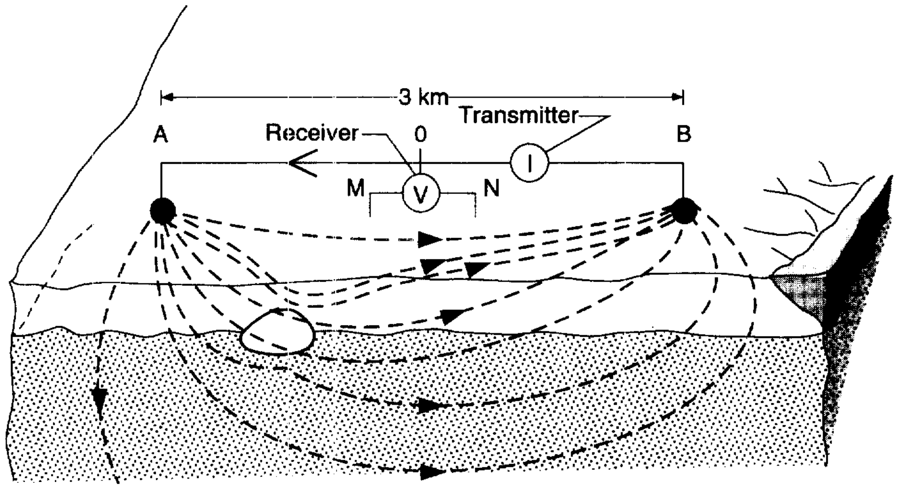

Fig. 17. An electric survey. Electric current is injected into the ground through electrodes A and B, and the voltage difference between electrodes M and N is measured. The electric resistivity of layers at depth is obtained as a consequence. The larger the distance between A and B, the deeper the depth of investigation.

- verify the existence of high-temperature fluids in areas without surface manifestations, but in which the geostructural and hydrogeological situation is favourable to hydrothermal circulation;
- more precisely site deep drilling in areas that are considered potentially productive;
- delineate the boundaries of geothermal fields that have been identified, so as to avoid drilling of dry holes in non-productive marginal areas;
- acquire data for evaluation of the geothermal potential of the field.

Heat flow measurements are made by drilling small-diameter (4 inches; 10 cm), shallow wells (generally <300 m), the number of which depends on local conditions and on the results one wants to achieve. Generally, heat flow is measured every 10–25 km^2. The depth of the wells must be such as to avoid the effects of propagation of the annual surface thermal variations, which are negligible beyond 200 m, and the thermal disturbances caused by the circulation of shallow groundwaters.

The geothermal gradient is obtained from temperatures measured with electric thermometers at various depths along a well. Temperature logging is quick and relatively inexpensive. The thermal conductivity of the rocks in the interval in which the gradient has been measured is usually determined by laboratory measurements on core samples. The product of the gradient and conductivity gives the heat flow.

Sometimes gradient values alone are sufficient to give the information required. However, this is possible only if the survey is carried out in areas that are lithologically homogeneous at depth, in which the thermal conductivity can be considered constant.

In geothermal areas the heat flow is higher than the general background level, so that high heat flow values are a good indicator of underlying geothermal resources (Fig. 18).

Exploratory wells

The final stage of an exploration survey is exploratory well drilling. Usually the final diameters of these wells are of the order of 8 inches (20 cm) or less, allowing the insertion

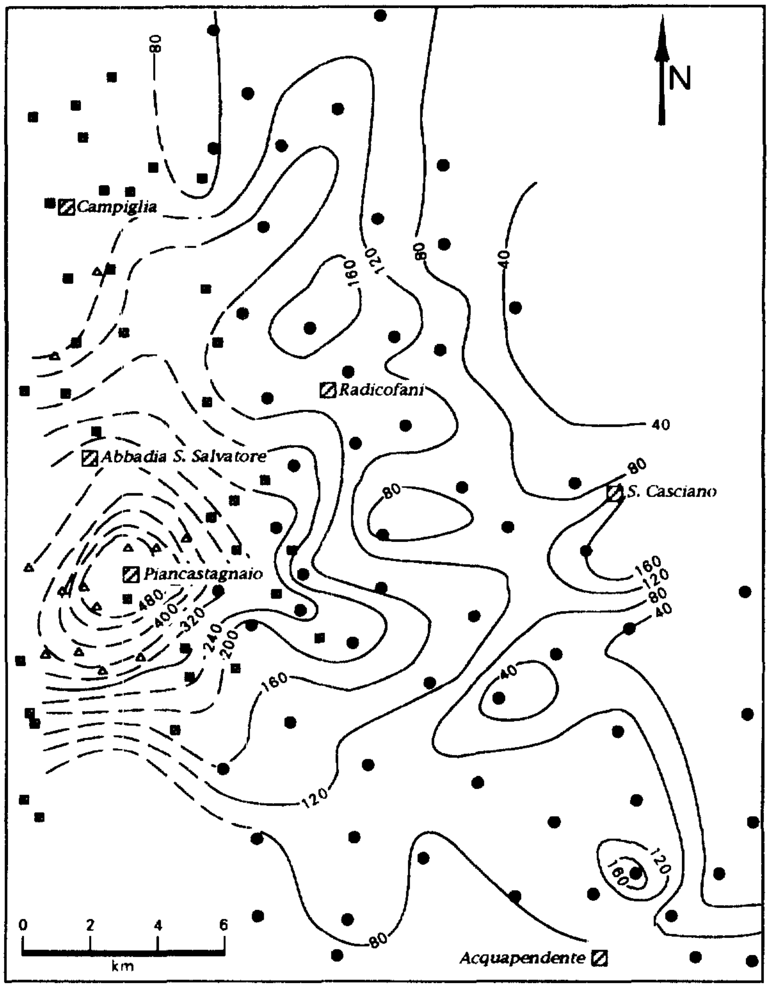

Fig. 18. A thermal-measurement survey, showing heat flow in an Italian geothermal area (Mt. Amiata, Tuscany). Note the very high values of heat flow at Piancastagnaio, where the geothermal field producing electricity is located. Heat flow in in mW/m^2; triangles show productive wells; black dots show the shallow wells (35 m) used for heat flow measurements. (From Ref. [28].)

of special logging tools to measure various parameters from the surface to total depth, and sometimes to carry out fluid production tests. A pump may be lowered into a shallow hot water well some hundreds of metres deep, and compressed air (gas lift) may be injected in deeper hot water wells.

Since most geothermal reservoirs are made up of fluid-filled fractures, it is essential that an exploratory well intersects as many fractures as possible. In some cases it may be necessary to redrill the well at an angle in order to intersect the natural fracture pattern. Since natural fractures are related to tectonic activity (folding and faulting), the siting of exploratory wells is greatly dependent on our geological interpretation of the local structural conditions.

DRILLING, EXTRACTION, AND DISTRIBUTION OF FLUIDS

High-temperature wells ($>150^{\circ}C$)

Drilling and completion of wells are the most critical operations in the development of a geothermal project. Drilling for geothermal fluids is similar to rotary drilling for oil and gas (Fig. 19). However, geothermal drilling is generally more difficult than in oil and gas operations due to the nature of the rock being penetrated and the higher temperatures and corrosive nature of the fluids. The rock is usually harder, metamorphic or igneous rather

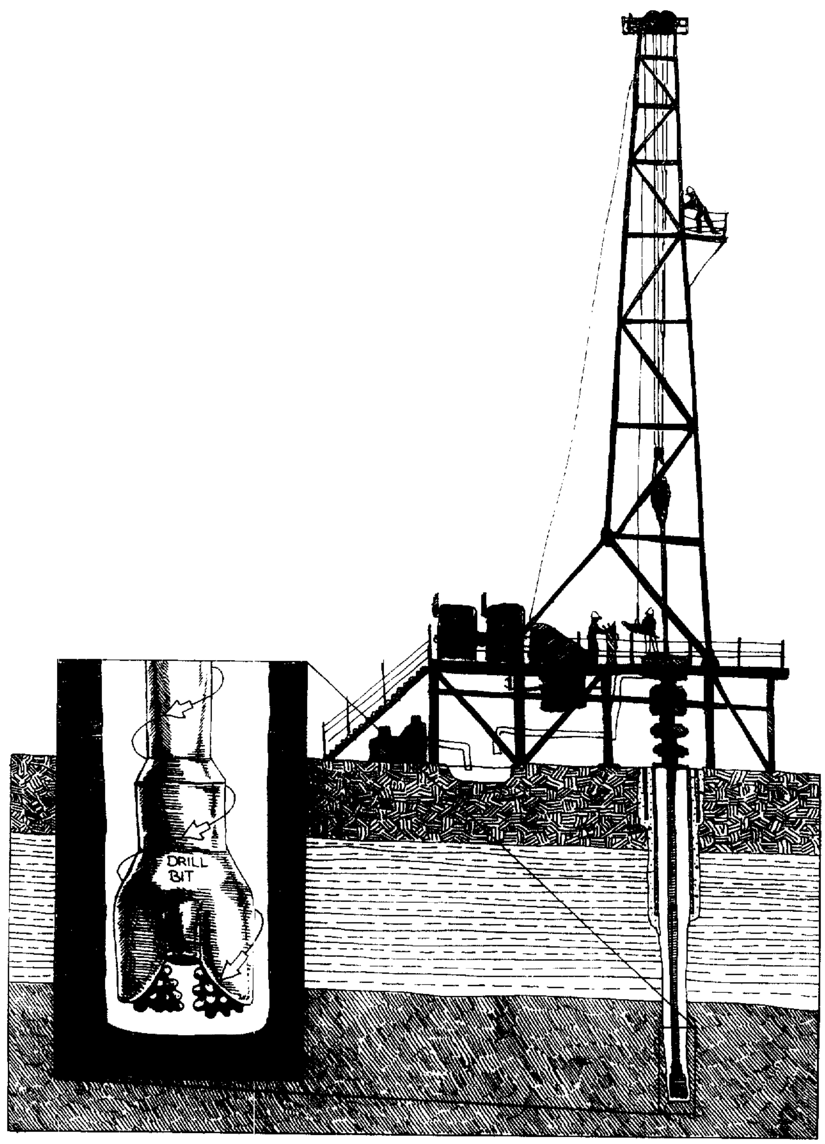

Fig. 19. A drilling rig and drilling bit. The bit is lowered to the ground and turned. As it turns, rock is chipped away. (From Ref. [29].)

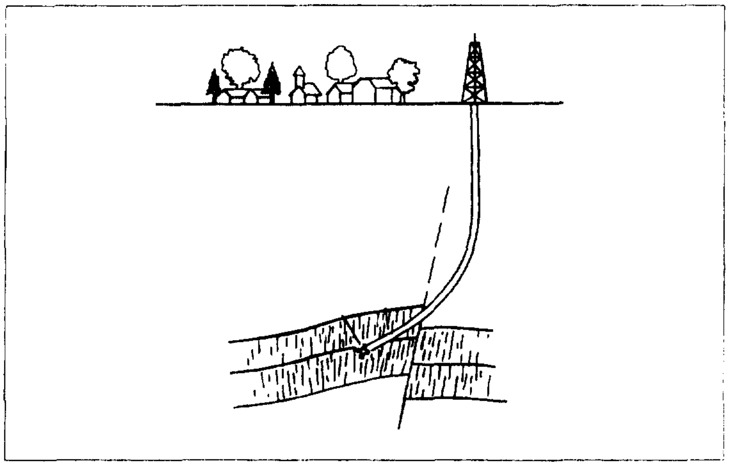

Fig. 20. Scheme of a directionally drilled well. This technique is used when the area directly above the drilling target is unavailable. (From Ref. [30].)

than sedimentary, and the high temperatures associated with geothermal wells affect the circulation system and the cementing procedures as well as the design of the drill string and casing. To prevent blow-outs of high-temperature wells during drilling, safety devices called blow-out preventers are used.

Mud is generally used as the drilling fluid, but the use of air instead of mud makes drilling much faster and cheaper and has been adopted frequently in recent years. One major obstacle in air drilling in geothermal areas is its unsuitability in formations carrying excessive water or in formations that tend to collapse.

Directional drilling techniques are used in areas where the surface directly above a drilling target is unavailable, when a well pad cannot be constructed for economic or environmental reasons, or when a single pad is to be used for several wells (Fig. 20). The angle is established and maintained by utilising a downhole turbine drill. Directionally drilled wells cost about 25% more than vertically drilled wells, in part because of slower penetration rates.

Due to the hardness of the rock, and the high probability of encountering lost-circulation zones where drilling fluids can disappear into the rock fractures, the cost of drilling can run as high as 50% of the total cost of a project. It ranges between US$800 and 1200 US$/m (1994), and commercial well depth is generally set at a maximum of 3 km.

Drilling success is, on average, 50% in developed geothermal fields. A single good well with an output of 60,000 kg/h of steam can sustain a 6 MW_e power station (Figs 21 and 22). However, the world figures from 29 producing fields and 2230 wells are lower, the range of power is 0.3–4.8 MW_e per well, and the weighted average 1.9 MW_e per well [31].

Low-temperature wells (< 150°C)

Drilling and casing* of a low-temperature well is probably the most expensive activity in geothermal projects for non-electrical uses. Present drilling technology is expensive, and

* The casing is a heavy metal pipe, lowered into a well during drilling and cemented into place. It prevents the sides of the hole from caving in, loss of drilling mud or other fluids into porous formations, and lateral ingress of cold unwanted fluids from entering the well.

Fig. 21. Drilling rig and controlled blow-out of a geothermal steam well. The well has crossed the impermeable cover and entered the reservoir, Larderello area, Italy.

the costs are rising rapidly. Costs of all wells increase exponentially with depth. The cost of drilling into many low-temperature geothermal reservoirs will make them uneconomic for production. Also, added to the actual cost of drilling are the costs for land acquisition and geological surveys.

The technology required for drilling into low-temperature geothermal reservoirs is similar to that used for groundwater wells. The primary aspect when drilling into these reservoirs is cost, and low-temperature wells deeper than 2 km are generally not considered economic.

Fig. 22. A steam well freely discharging into the atmosphere; the output is 324 t/h of superheated steam. Travale geothermal field, Tuscany, Italy.

Extraction of fluids

The flow-rate from, and the performance of a geothermal reservoir are functions of many parameters. Among these are the volume and type of the fluid in the aquifer, the rate of recharge (if any), the permeability of the rocks, the design of the drilled well and piping, and the type of completion equipment utilised (e.g. pumps in low-temperature wells).

Depending on the characteristics of the particular reservoir, the fluid may exist at the surface as a liquid, a vapour, or a mixture of the two, and may also include various dissolved gases and solid material. Thus, the type of equipment necessary to extract the fluid from its reservoir will depend on the enthalpy–pressure characteristics of the fluid (Fig. 12) and its salt content. For low-temperature fluids, of interest in non-electrical applications, we will generally be looking for fluid in the liquid phase.

Well testing and reservoir modelling

Electrical, mechanical, or temperature-sensitive devices are lowered into the well to record various physical parameters. Well logging is now a consolidated technique, developed over

many decades by the oil industry. Due to the high temperature and hostile chemistry (HCl, H_2S, HF, etc.) found in geothermal fluids, many conventional well-logging methods must be modified to work in the geothermal environment.

Depending on the well conditions, logging can provide information on temperature, depth, pressures at various points, types of rock and their permeability, porosity, and fluid content. Fractures met by the well at depth can be located, and fluid production zones can be identified [30]. This information is of primary importance to reservoir engineers and to geologists, geophysicists and geochemists, who use it to confirm and refine their interpretation of the deep geological structures and of the thermal and hydrogeological conditions in the subsurface, hypothesised beforehand by means of geological, geophysical, and geochemical surveys carried out at the surface.

The most difficult but fundamental parameters to be determined are the size of the reservoir and its energy potential. It is therefore evident that long production tests must be carried out correctly as they are the key to decide whether further investments are advisable in the field, and the best economic use of the resource. To recover exploration and development costs, a geothermal field must keep the fluid extraction rate reasonably constant over many years, at least several decades. Geothermal reservoir models are of great help in providing this information.

Geothermal reservoir modelling provides quantitative estimates of future fluid flow from wells exploiting the reservoir. The predicted well performance is determined by the future fluid state (pressure, temperature, enthalpy, etc.) in the reservoir, and results are usually presented in the form of changes in the reservoir [32]. A quantitative model must be validated against field data. The distinctive test of a model is its ability to reproduce known behaviour. Mathematical models are implemented with the help of computers. With a good model the optimum fluid production and the subsequent reinjection rate of the waste back into the peripheral parts of the reservoir can be quantified and projected over several years.

Distribution of fluids

Production-gathering systems transport the produced fluids, steam or water, from the wells to the power plants or other utilisation facilities, such as buildings or greenhouses. Vapour-dominated reservoirs produce dry steam, which goes directly from the wells to the power plants. In water-dominated reservoirs which produce water and steam (and not hot water only), the fluid from the wells is sent into separators, located on the well pads. The separator allows a portion of the fluid (15–20%) to flash into steam, which is then directed through pipelines to the power plant (Fig. 23). The condensed steam and the remaining waste water are then generally discharged back into reinjection wells.

In the non-electrical uses (direct uses) of geothermal energy, a hot water distribution network is required. Its cost may represent a major part of the total system cost. The network is an assembly of piping that varies in size throughout the system depending on the flow-rates through the various branches (Fig. 24). These systems also require pumps, valves, metres, expansion joints, and the controls necessary for reliable operation of the network. The system is generally thermally insulated to prevent excessive heat loss and temperature drop in the fluid.

GEOTHERMAL ENERGY UTILISATION

Practical uses of geothermal energy, for bathing, washing and cooking, date back to prehistory. The Etruscans, Romans, Greeks, Indians, Chinese, Mexicans, and Japanese

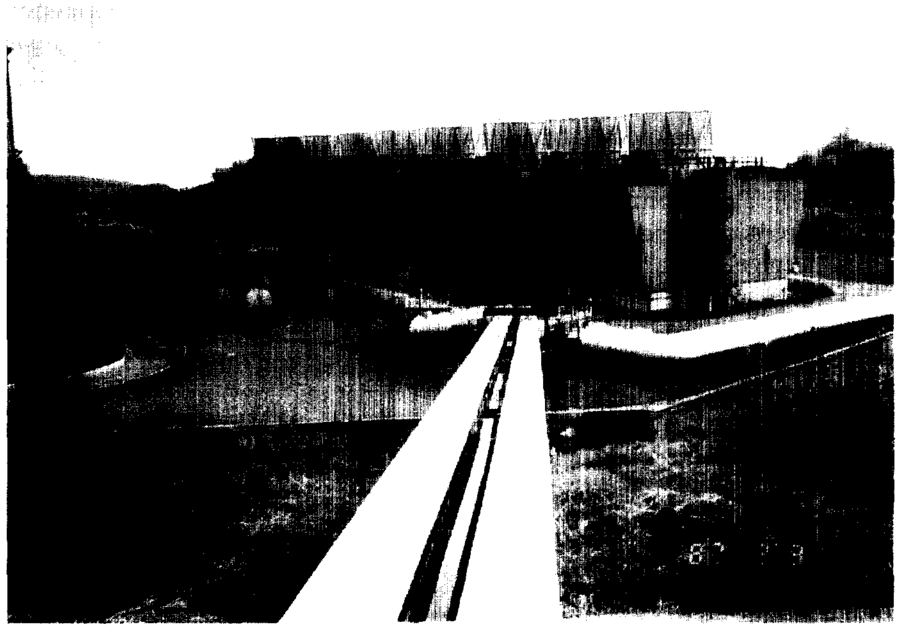

Fig. 23. Pipelines feeding steam to the Tongonan power plant, 115 MW_e, in the Philippines. The cooling towers (the nine cylinders) are equipped with fans electrically driven.

have all left evidence that they used hot water in ancient times, where these waters were commonly thought to have healing properties. Since the 8th century AD, the Japanese have used thermal waters for body purification, which is the first step in the purification of the spirit, and many hot spring sites have temples dedicated to the Buddha of Medicine. The Romans also used thermal springs for recreational purposes. They built spas all over the Mediterranean area (Fig. 25), and to the furthest boundaries of their empire, for example at Bath in England, thus spreading their knowledge of the beneficial effects of thermal waters. The Roman poet Lucretius, who lived a few decades before Christ, mentions amongst natural phenomena the thermal springs of the Vesuvius region in Book VI (verses 747–748) of his poem *De Rerum Natura* (On the Nature of Things), and made the first attempt at giving a scientific explanation, rather than supernatural, of these natural phenomena. In the Middle Ages, Arabs and Turks developed and diffused the traditional use of thermal baths, later known as Turkish baths, whose rich and sensual atmosphere is depicted by the French painter Ingres in his masterly *The Turkish Bath* (1863, Louvre). These uses were to lead the way to the modern balneological industry.

Space heating with geothermal waters was, however, to come much later. Fridleifsson and Freeston, in their excellent paper on geothermal research and development [21], tell us that although primitive pipelines were built by the Romans and the Chinese to convey water and steam for baths, it was only when metal pipes and radiators became common that geothermal energy was used for space heating. Even in Iceland, where hot springs are abundant and the mean annual temperature is 4°C, and Reykjavik is at present the only capital city of the world heated entirely by geothermal energy, geothermal space heating was first installed in a house in 1909.

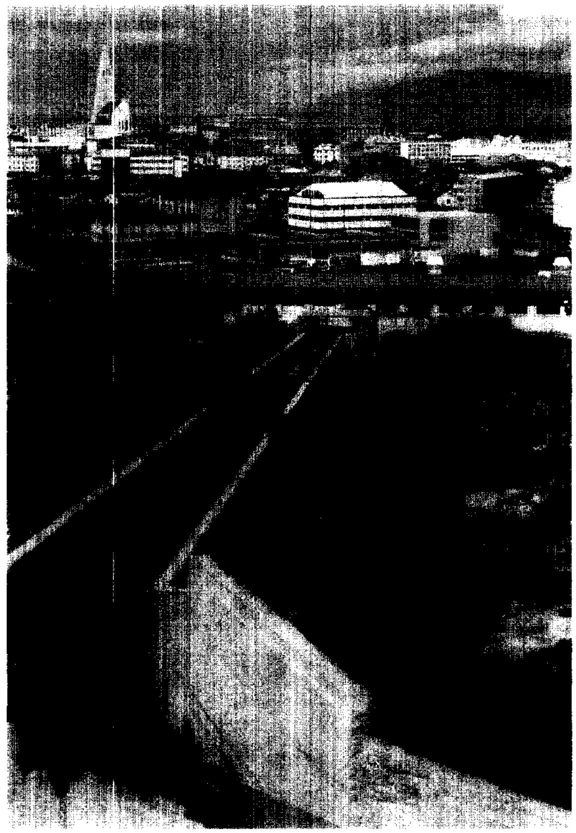

Fig. 24. Insulated pipes of the geothermal water distribution network for district heating, Reykjavik, Iceland.

The earliest residential heating in the world by geothermal water was in Chaude Aigues (France) in the 14th century. The first municipal district heating system using geothermal water was set up in Reykjavik, Iceland, in 1930. At present, 85% of the total population of Iceland live in houses heated by geothermal water. Large-scale district heating systems using geothermal water have been built in many countries, such as France, Russia, Georgia, China, Italy, and the U.S.A.

Geothermal waters were first used in greenhouse heating in Iceland in the 1920s; now hundreds of hectares of greenhouses are operating throughout the world. In the last two decades geothermal heat has been used on an increasingly large scale in animal husbandry, fish farming, crop drying, and soil heating. Air conditioning using geothermal steam was first developed in a hotel in Rotorua, New Zealand, in the late 1960s.

Mineral extraction from geothermal fields is recorded from Etruscan times, as documented by numerous archaeological finds, especially the fine ceramics whose glazes and paints contain traces of boric salts coming from the hot boric waters of that part of Tuscany known as the boraciferous region (Larderello). A prosperous boric acid industry, which lasted 150 years, was created in the Larderello area in 1818 extracting boric salts from the geothermal waters of the area (Fig. 26). In Iceland geothermal fluids were used to extract

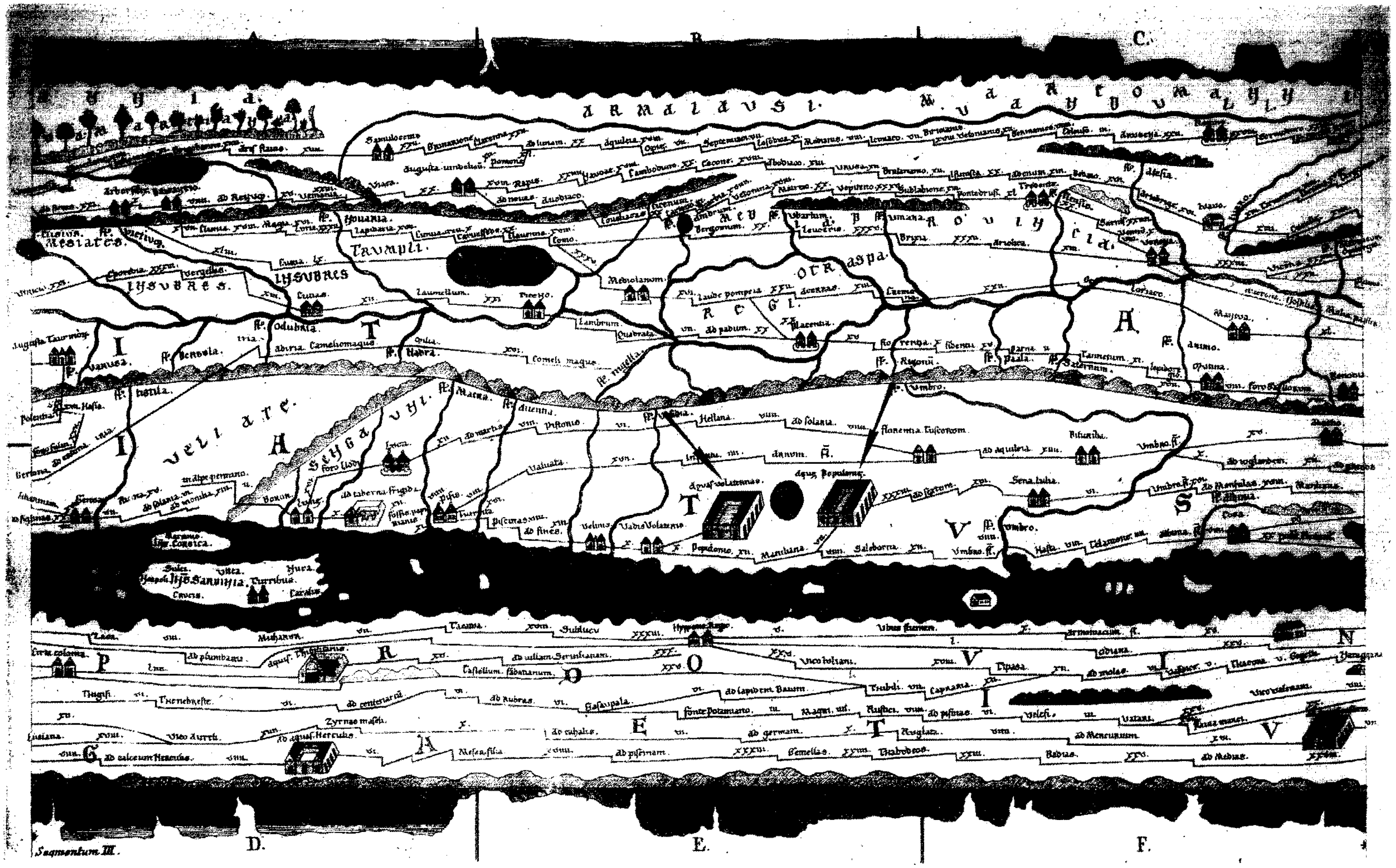

Fig. 25. Part of the *Tabula Itineraria Peutingeriana*, 3rd century AD, showing the main roads of the Roman Empire and the spas in the Larderello area (Tuscany, Italy) called *Aquas Volaternas* and *Aquae Populaniae* (marked by arrows). (Courtesy of ENEL, Italy).

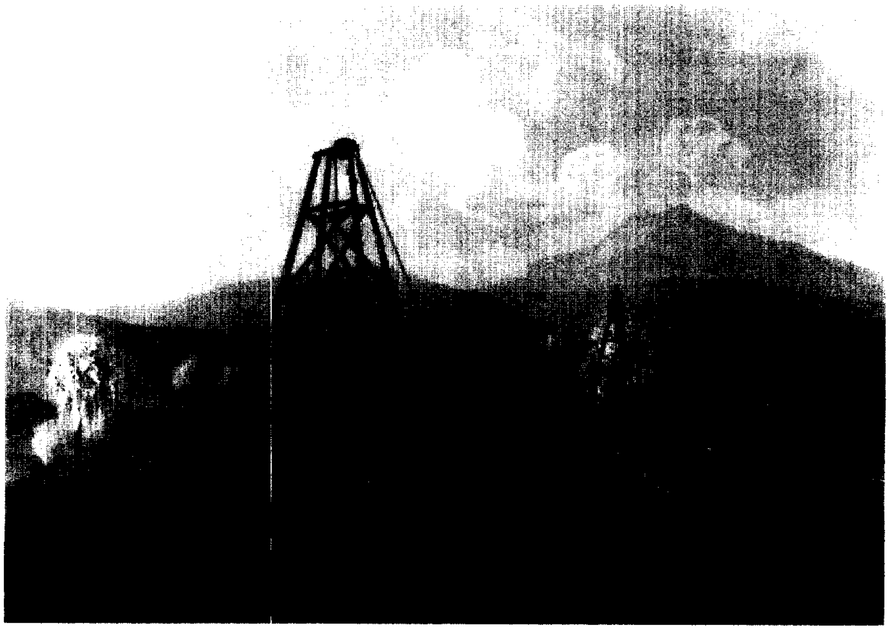

Fig. 26. A hand-driven drilling rig to extract boron-rich waters in the Larderello area (Tuscany), in an engraving of 1828. (Courtesy of ENEL, Italy).

salts from sea water in the 18th century, and in New Zealand a pulp and paper mill has been using more than 200 t/h of geothermal steam for processing the wood since the early 1950s. In China geothermal water has been used for its chemical properties in large-scale carpet dyeing.

Electricity generation from geothermal steam is a much more recent industry, dating back to the beginning of this century. In fact, commercial generation of electricity from geothermal steam began in Larderello, Tuscany, Italy, in 1913, with an installed capacity of 250 kW_e. However, the first experiments to make use of natural steam to generate electricity date back to 1904, when Prince Piero Ginori Conti coupled a steam engine to a dynamo to light five bulbs in his boric acid factories at Larderello. Since 1950 other countries have followed the Italian example, and at present electricity is generated from geothermal energy in 18 countries all over the world. The evolution in time of the worldwide geothermal installed electrical capacity is presented in Fig. 27.

It is now clear that geothermal utilisation is divided into two categories, i.e. electric energy production and direct uses. Figure 28 shows the minimum production temperatures generally required for the different types of utilisation. The upper and lower limits are, however, not stringent and serve only as guidelines. Conventional electric power production is limited to fluid temperatures above 150°C, but considerably lower temperatures can be used in binary cycle systems, also called organic Rankine cycles (in this case the outlet temperatures of the geothermal fluid are commonly above 85°C). The ideal temperature of thermal waters for space heating is about 80°C, but larger radiators in houses or the use of heat pumps or auxiliary boilers means that thermal water with temperatures only a few degrees above ambient temperature can be used beneficially [21].

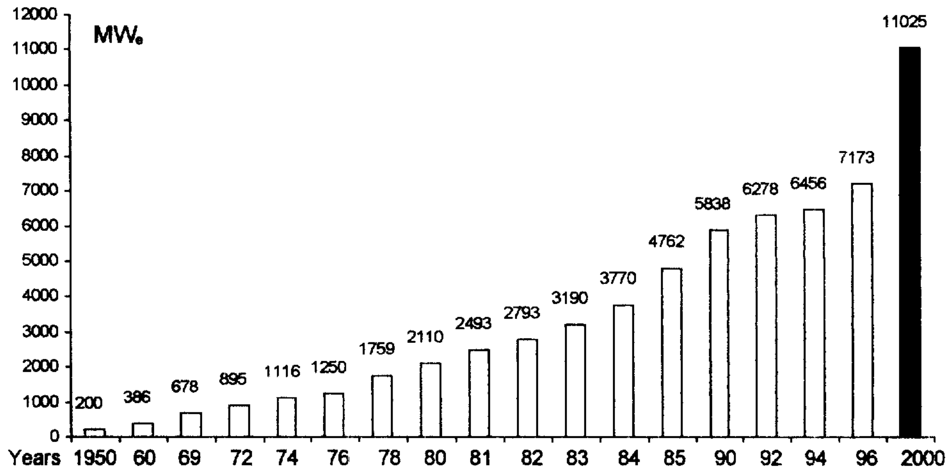

Fig. 27. Evolution of worldwide electrical installed capacity, and forecast to year 2000. (Forecast from Ref. [35].)

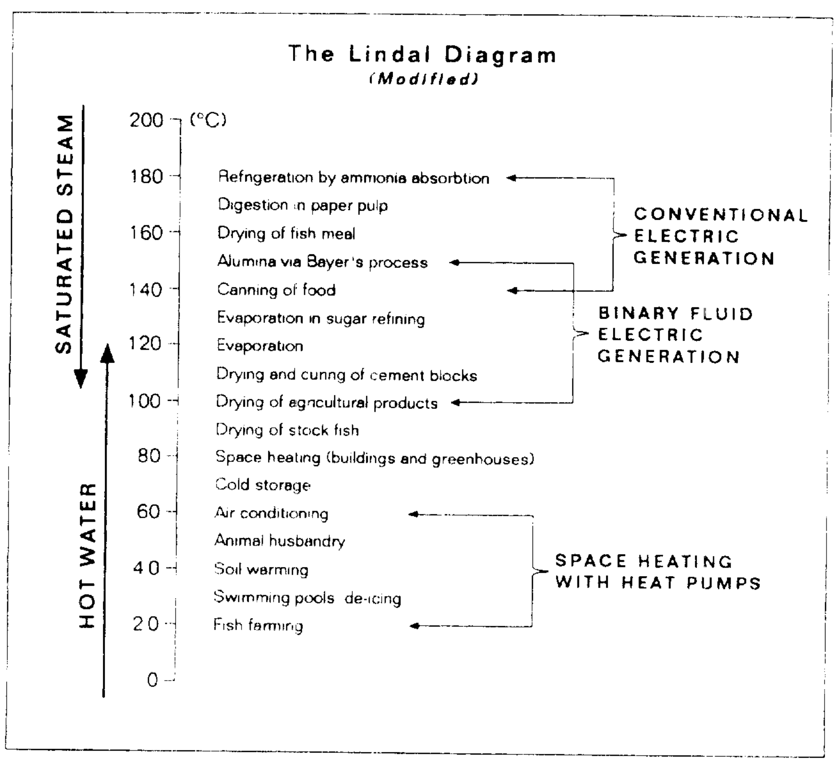

Fig. 28. The Lindal diagram of typical fluid temperatures for direct applications of geothermal resources. (From Ref. [21].)

ELECTRICITY FROM GEOTHERMAL FLUIDS

The world scenario

The December 1996 status of worldwide geothermal development is shown in Table 3, which lists the 18 countries in which electricity is generated from geothermal fluids. Forecasts for the year 2000 placed the geothermal electric capacity at 11,025 MW_e [35]. Table 4 also shows the geothermal electric capacity per geographical regions. Figure 27 shows the evolution of the world geothermal electric capacity.

The world geothermal electric capacity installed by December 1996 was 7173.5 MW_e, representing 0.4% of the world's electric capacity. The total electricity produced worldwide

Table 3. Geothermal electric installed capacity in the world in 1985, by December 1996, and forecast for the year 2000 (1985 data from Ref. [33]; 1996 and 2000 data from Ref. [34] and [35])

Countries	(MW_e) 1985	Dec. 1996	2000
United States	2022	2816.7	3395.0
Philippines	894	1444.0	2291.0
Mexico	645	753.0	1144.0
Italy	519	625.7	852.5
Japan	215	528.7	600.0
Indonesia	32	309.5	1206.5
New Zealand	167	286.0	440.0
El Salvador	95	110.0	165.0
Nicaragua	35	70.0	185.0
Costa Rica	—	60.0	170.0
Iceland	39	50.0	140.0
Kenya	45	45.0	109.0
China	14	32.5	81.0
Turkey	21	20.4	125.0
Russia	11	11.0	110.0
France (Guadaloupe isl.)	5	5.0	5.0
Portugal (Azores islands)	3	5.0	5.0
Argentina	—	0.7	na
Thailand		0.3	0.3
India	—	—	1.0
Georgia	—	—	0.5
Total	**4762**	**7173.5**	**11,025.8**

Table 4. Geothermal electric capacity (MW_e) installed in different areas of the world in the years 1985 and 1996. (Data from Table 3).

Area	1985	%	Dec. 1996	%
Africa	45	0.9	45.0	0.6
Asia	1187	24.9	2346.4	32.7
Oceania	167	3.5	286.0	4.0
Latin America and Caribbean	780	16.4	998.7	13.9
North America	2022	42.5	2816.7	39.3
Europe and Atlantic	561	11.8	680.7	9.5
World	**4762**	**100.0**	**7173.5**	**100.0**

Table 5. Percentage of electric capacity from geothermal energy with respect to total electric capacity for some countries. The values of percentages are only suggestive of a trend because the data compared refer to different years. (Total capacity from Ref. [37]; geothermal capacity from Ref. [35])

	Total electric installed capacity, 1993 (MW_e)	Geothermal electric installed capacity 1996 (MW_e)	% of the total power installed
Industrialised countries			
U.S.A.	695,120	2816.7	0.4
Japan	205,140	528.7	0.2
Italy	61,630	625.7	1.0
New Zealand	7,520	286.0	3.8
Developing countries			
El Salvador	750	110.0	14.7
Philippines	6,770	1444.0	21.3
Nicaragua	460	70.0	15.2
Kenya	810	45.0	5.5
Mexico	28,780	753.0	2.6
Indonesia	12,100	309.5	2.5
Costa Rica	1,040	60.0	5.8

by the same period was 13,267 billion kWh [35, 36], 38 billion kWh were generated using geothermal fluids. This figure shows that geothermal energy plays a very minor role on the world energy scene.

However, if we distinguish between industrialised and developing countries, then the contribution of geothermal energy is entirely different. In the industrialised countries, where the installed electrical capacity reaches high figures (tens or even hundreds of thousands of MW_e), geothermal energy is unlikely, in the next decade, to account for more than one percent, at most, of the total (Table 5).

In developing countries, with an as yet limited electrical consumption but good geothermal prospects, electrical energy of geothermal origin could, on the contrary, make quite a significant contribution to the total: at the moment, for instance, 15% of the electricity in El Salvador comes from geothermal sources, 21% in the Philippines, 15% in Nicaragua, and 6% in Kenya and Costa Rica.

Efficiency of generation

The efficiency of the generation of electricity from geothermal steam ranges from 10 to 17%, about three times lower than the efficiency of nuclear or fossil-fuelled plants. Table 6 compares the efficiency of geothermal, nuclear, and fossil fuel-fired power stations. This

Table 6. Comparison of power station efficiencies. T_{max} is the maximum temperature of steam in the turbine

Energy source	Efficiency	T_{max} (°C)
Geothermal	10–17%	250
Nuclear	33%	330
Oil–Coal	38–45%	540

comparison shows that geothermal plants have the lowest efficiency values due to the low temperature of the steam, which is generally below 250°C.

Furthermore, geothermal steam has a chemical composition that is different from pure water vapour, because it generally contains non-condensable gases (CO_2, H_2S, NH_3, CH_4, N_2 and H_2) that have to be extracted from the condensers of power plants (Table 1). These gases are present in the steam in variable quantities (1–50 g/kg of fluid) and they reduce the efficiency of electricity generation.

Geothermal power plants require from 6 kg/kWh (if dry steam is available) to 400 kg/kWh of fluid (if hot water is used in binary cycle plants), the latter referring to electricity generated from low-to-medium temperature resources (85–150°C).

Electricity generating cycles

The simplest and cheapest of the geothermal cycles used to generate electricity is the *direct-intake non-condensing cycle* (Fig. 29). Steam from the geothermal well is simply passed through a turbine and exhausted to the atmosphere: there are no condensers at the outlet of the turbine (Fig. 30). Such cycles consume about 15–25 kg of steam per kWh generated. Non-condensing systems must be used if the content of non-condensible gases in the steam is very high (greater than 50% in weight), and will usually be used in preference to the condensing cycles for gas contents exceeding 15%, because of the high power that would be required to extract these gases from the condenser.

Condensing plants, with condensers at the outlet of the turbine and conventional cooling towers (Figs 31 and 32), show a much lower consumption, only 6–10 kg of steam per kWh generated, but the gas content of the steam must be less than 15%. The specific consumption

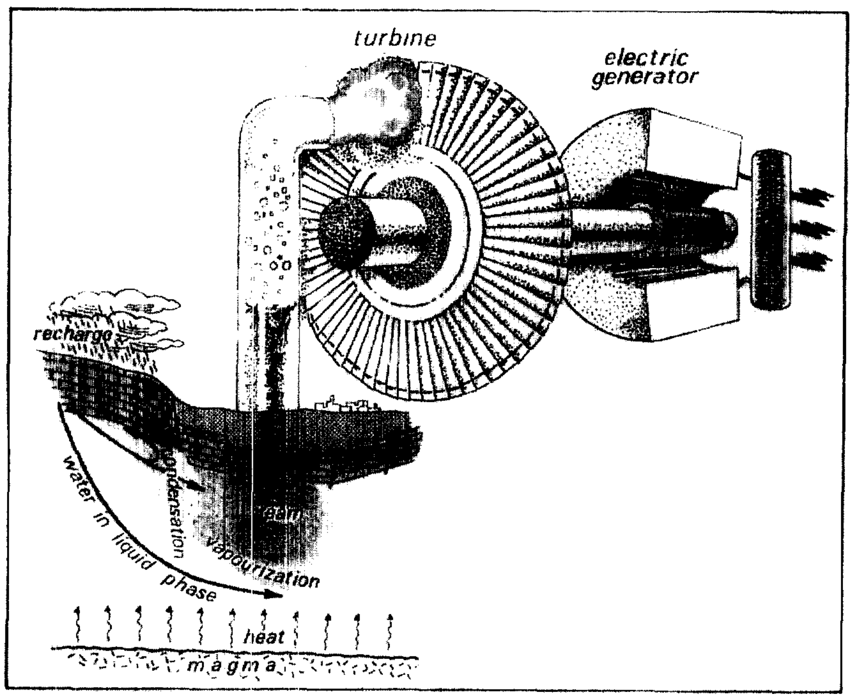

Fig. 29. Generation of electricity with geothermal steam.

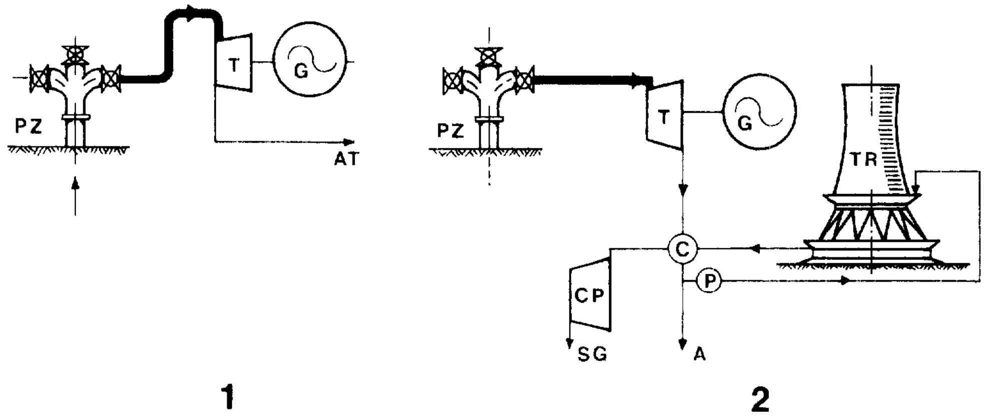

Fig. 30. Geothermal cycles for generation of electricity. (1) Direct-intake exhausting-to-atmosphere turbine. (2) Direct-intake condensation turbine and cooling tower. PZ, geothermal well; T, turbine; G, generator; AT, exhaust to atmosphere; CP, compressor-extractor of non-condensable gases contained in the geothermal fluids; SG, gas discharge; C, condenser; P, pump; A, water discharge; TR, cooling tower.

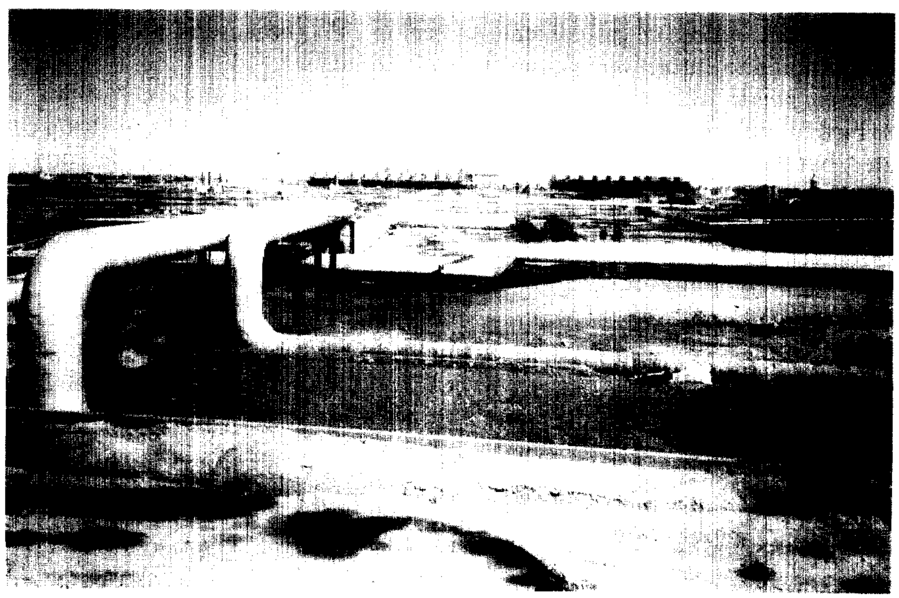

Fig. 31. Pipelines to power plants, Cerro Prieto geothermal field, Mexico.

of steam of these units is greatly influenced by the turbine inlet pressure: for pressures ranging from 5 to 20 bars (1.5–2.0 MPa), the consumption is close to 6 kg/kWh. For pressures ranging from 5 to 15 bars (0.5–1.5 MPa) the consumption is from 9 to 7 kg/kWh, and it becomes much greater for even lower pressures [38].

In power plants where electricity is produced from dry or superheated steam (vapour-dominated reservoirs), steam is piped directly from the wells to the steam turbine. This is a well-developed, commercially available technology, with typical turbine-size units in the 20–120 MW_e capacity range. Recently, a new trend of installing modular standard generating units of 20 MW_e has been adopted (Italy) (Fig. 33).

Fig. 32. Geothermal power plant at Palinpinon field, Philippines.

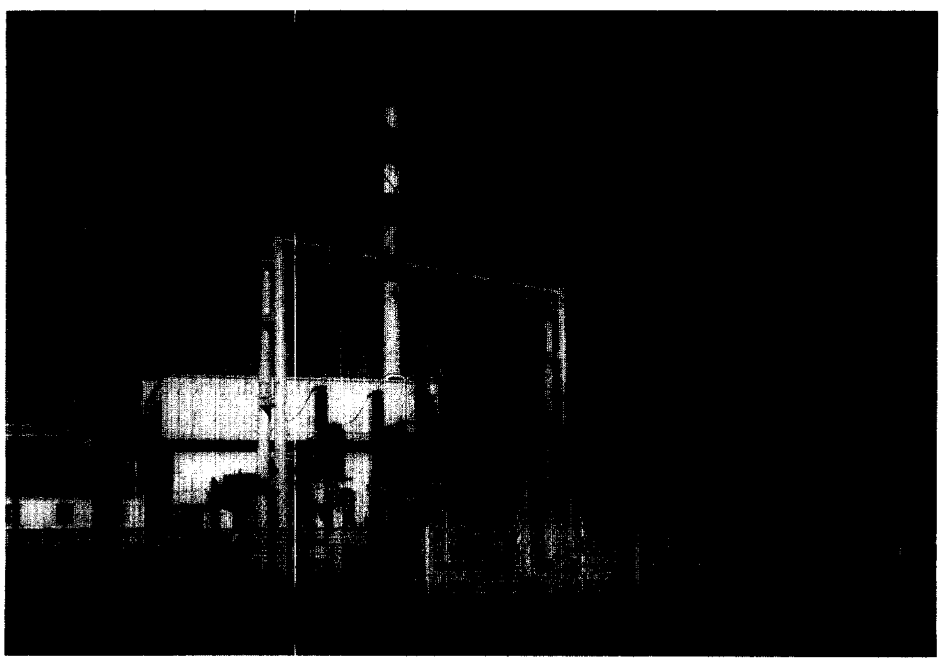

Fig. 33. A new modular geothermal generating unit of 20 MW_e adopted in Italy, Larderello area.

Vapour-dominated systems are less common in the world; steam from these fields has the highest enthalpy (energy content), generally close to 670 kcal/kg (2800 kJ/kg) (Fig 12). At present these systems have been found only in Indonesia, Italy, Japan, and the U.S.A. These fields produce about half of the geothermal electrical energy of the world. Water-dominated fields are much more common. Flash steam plants are used to produce energy from these fields that are not hot enough to flash a large proportion of the water to steam in surface equipment, either at one or two pressure stages. Commercially available turbogenerator units are commonly in the range 10–55 MW_e. Modular standardised units of 20 MW_e are being implemented.

If the geothermal well produces hot water instead of steam, electricity can be still be generated, provided the water temperature is above 85°C, by means of *binary cycle plants*. These plants operate with a secondary, low-boiling-point working fluid (freon, isobutane, ammonia, etc.) in a thermodynamic cycle known as the organic Rankine cycle. The working fluid is vaporised by the geothermal heat in the vaporiser. The vapour expands as it passes through the organic vapour turbine, which is coupled to the generator. The exhaust vapour is subsequently condensed in a water-cooled condenser or air cooler and is recycled to the vaporiser by the motive fluid cycle pump (Figs 34 and 35). The efficiency of these cycles is even lower: between 2.8 and 5.5%. Typical unit size is 1–3 MW_e. However, the binary power plant technology has emerged as the most cost-effective and reliable way to convert large amounts of low-temperature geothermal resources into electricity, and it is now well known that large low-temperature reservoirs exist at accessible depths almost anywhere in the world.

The power rating of geothermal turbine/generator units tends to be smaller than in conventional thermal power stations. Most commonly the units are 55, 30, 15, 5 MW_e, or smaller. One of the advantages of geothermal power plants is that they can be built economically in relatively much smaller units than, for example, hydropower stations. In developing countries with a small electricity market, geothermal power plants with units from 15 to 30 MW_e can thus be more easily adjusted to the annual increase in electricity demand than, say, 100 or 200 MW_e hydropower plants. The reliability of geothermal power plants is very good, the annual load factor and availability factor are commonly about 90%, and geothermal fields are not affected, for example, by annual or monthly fluctuations in rainfall, since the essentially meteoric water has a long residence time in geothermal reservoirs [21].

Cost of electricity generation

In geothermal development for the generation of electricity, about 50% of total costs are related to the identification and characterisation of reservoirs and, above all, to the drilling of production and reinjection wells. Of the remainder, 40% goes to power plants and pipelines, and 10% to other activities.

The cost of the geothermal kWh is characterised by a high share of capital cost (steam field and plants), and relatively low operation and maintenance costs. This is apparent when the field developer is also the plant operator. On the other hand, when steam is supplied with a sale contract to the plant operator, its price may be linked to other factors (such as the cost of fossil fuels), so that the share of operating costs may not be as low as in the former case.

The investment share in the cost of the geothermal kWh is due to the following activities:

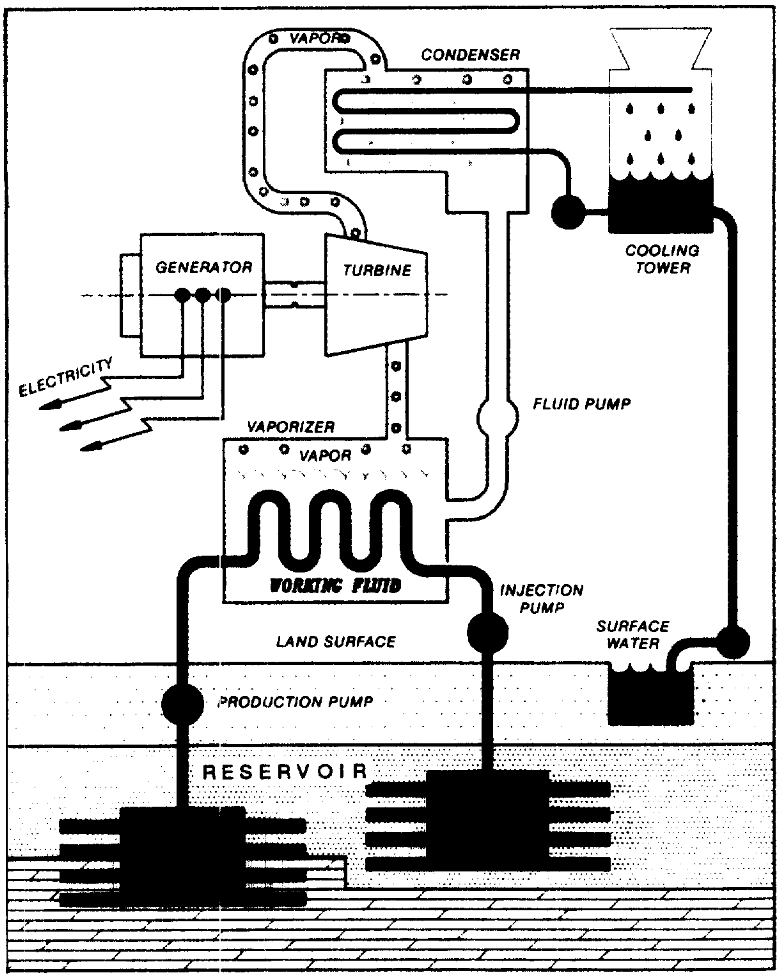

Fig. 34. The binary geothermal power cycle can produce electricity from hot water (above 85°C). The cycle operates with a secondary, low-boiling working fluid (freon, isobutane, ammonia, etc.), in a thermodynamic cycle known as the Organic Rankine Cycle. The geothermal fluid is extracted from the reservoir and injected back into the reservoir without getting into contact with the working fluid.

(1) the surface exploration and the surveys preliminary to deep drilling aimed at identifying the possible existence of a geothermal field;
(2) the drilling of exploration, production, and reinjection wells (including non-productive wells): the first are necessary for the characterisation of the fluid and the field, while the others serve for its exploitation and development;
(3) the construction of surface installations: steam pipelines, water pipelines, fluid treatment installations and power plants.

Point 3 can vary from 1500 to 1700 US$/kW, in relation to the size of the turbine, pipeline network, etc. Point 2 may equal or double point 3, and point 1 is generally negligible compared to the other points. Hence, the cost of realising a generating geothermal plant may vary, on average, from 2000 to 6000 US$ per installed kW, all costs included. In any

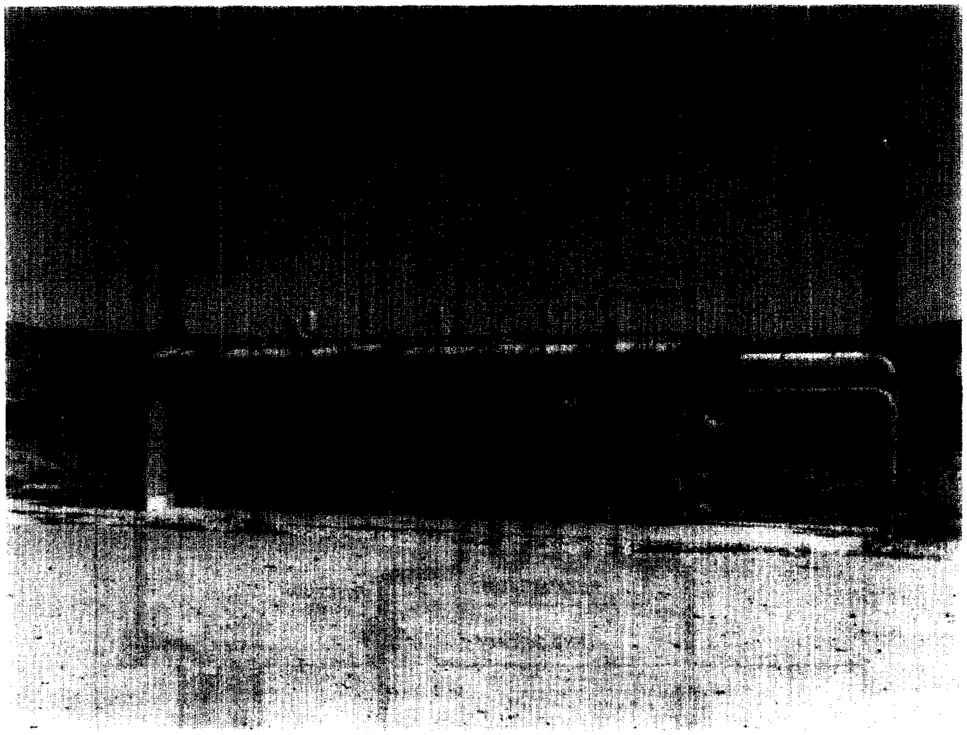

Fig. 35. Ormat geothermal binary power plant exploiting hot water, 800 kW_e Wabuska, Nevada.

case, the incidence of investments on the cost of the produced kWh is considerable, depends on the annual rate of interest, and is affected by the lapse of time necessary to drill the wells and to build the power plant [38].

Conversely, the cost of operation and maintenance, including the non-routine maintenance of the geothermal field, done by periodic drilling of new wells to offset the natural depletion of hydrothermal fields, represents only 10–20% of the total cost of the kWh. The 80–90% is therefore represented by capital amortisation. The production cost of the kWh can thus vary in the range 3–12 cents US$ (Table 7) [38, 39].

The cost of the power plant, alone, is instead as follows.

Condensing geothermal power stations (5–10 MW_e) cost 1485–1690 US$/kW (1993), while small generating plants with atmospheric exhaust (2.5–5 MW_e) range between 1050 and 1250 $/kW [40]. It is true that plants with atmospheric exhausts are cheaper than plants with condensing exhaust, but their steam consumption is higher: 15–25 kg/kWh compared to the 6–10 kg/kWh of condensing cycles. These condensing exhaust plants, with cooling towers, only yield a higher efficiency if the steam content of the non-condensable gases (CO_2, H_2S, NH_3, CH_4, and H_2) as mentioned earlier, is below 15%.

Binary plants, exploiting hot water, are even more expensive: around 1900 US$/kW (1 MW_e in size).

A recent analysis on the cost of electric energy from oil and from geothermal [41] shows that at a cost of an oil barrel of US$15 any geothermal field with a productivity over 3 MW_e per well can produce electricity more cheaply than a thermal power plant. However,

Table 7. Estimated production cost of a kWh (1992) for different energy sources

Source	Cost (cents U.S.$/kWh)
[1] Oil/coal/nuclear	6
[1] Hydro	3–9
[2,3] Geothermal steam (hydrothermal-flash)	3–12
[3] Wind	11
[3] Solar thermal	15
[3] Biomass	11
[3] Cogeneration	6

[1] Ref. [42]; [2] Ref. [38]; [3] Ref. [39].

as the world average productivity is 1.9 MW_e per well, it can be assumed that the cost of electricity from oil with oil prices at $15/bbl may be the same in some cases as from geothermal energy. Even if this is the case, the advantage of geothermal for some countries lies in the fact that the hard currency needed for oil importation can be saved by utilising the indigenous resource instead. Estimated costs of the kWh from different energy sources are given in Table 7, and electricity generated worldwide in 1994 from renewable energy is shown in Table 8, where geothermal ranks first with 89% of the total.

NON-ELECTRICAL USES OF GEOTHERMAL ENERGY

The utilisation of natural steam for electricity generation is not the only possible application of geothermal energy. Hot waters, that appear to be present in large parts of all the continents can also be exploited and offer interesting prospects for the future, especially in space heating and industrial processes (Figs 36 and 37).

The thermal power installed for non-electrical uses of geothermal energy worldwide at the end of 1994 has been estimated at 8664 MW_t, for the most part for domestic and greenhouse heating. These applications utilise 37,000 kg/s of fluid, contributing to a saving of about 3 million tons of oil per year. Table 9 shows the installed thermal power and flowrates of non-electrical uses worldwide [45]. The load factor is influenced by a number of

Table 8. Electricity from renewable energy in the world (excluding hydropower) in 1994. Installed capacity and production, biomass contribution probably consistent, but statistics not available. Data were shown at the 16th World Energy Council in Tokyo, October 1995. (From Ref. [43], modified)

	Electricity from renewable energy in 1994			
	Installed capacity		Production per year	
	(MW_e)	(%)	(GWh)	(%)
Geothermal	6456	61	37,976	86
Wind	3517	33	4,878	11
Solar	366	3	897	2
Tidal	261	3	601	1
Total	**10,600**		**44,352**	

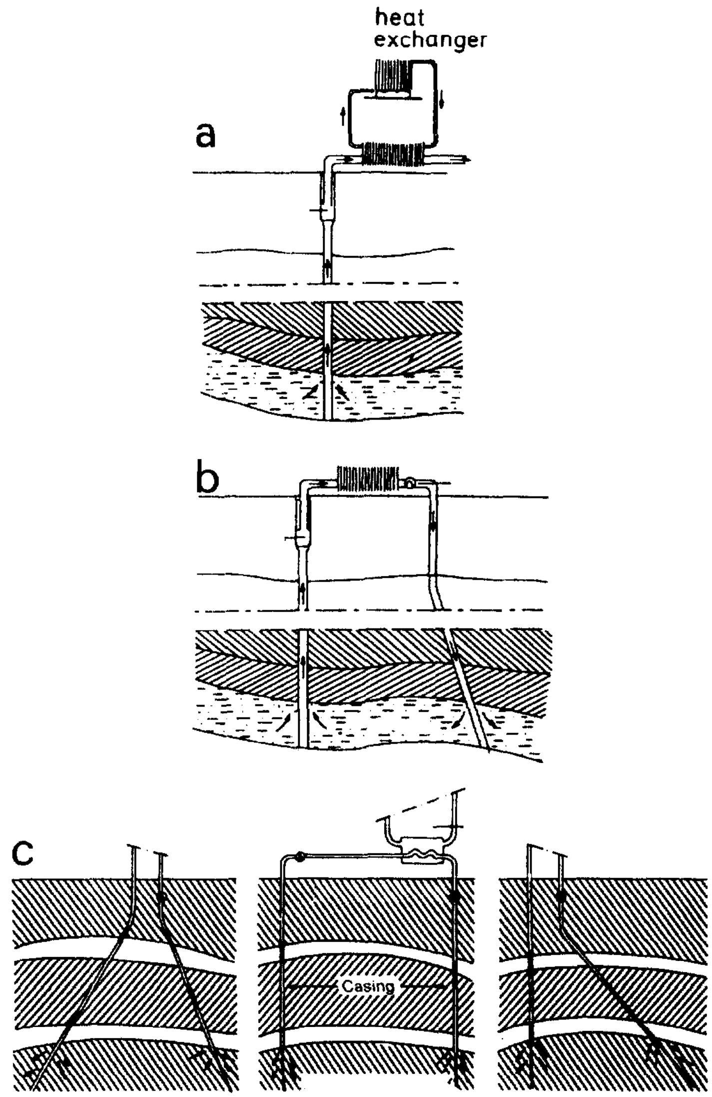

Fig. 36. Various schemes to extract hot water from a reservoir. (a) Single well, no reinjection into the reservoir, used with waters of low salinity, not polluting. (b) Two wells, a "doublet": on the left the production well, on the right the reinjection well, deviated to avoid the cooling of the production area. (c) other examples of doublets: on the right the production well. (From Ref. [44].)

things, including local climate, process use and commercial interests, so the average values given by Freeston are typical values only.

Figure 38 shows the distribution of annual energy utilisation by use. Bathing here refers mainly to swimming in thermal mineral pools, and pools heated by geothermal fluids. Space heating, which includes both district heating and the supply of domestic hot water, is the largest user of geothermal fluids (Fig. 39). Heat pumps represent 13% of the total, and are used for the most part in Switzerland and the U.S.A.

In geothermal fluid utilisations the time lapse between the discovery of a resource and

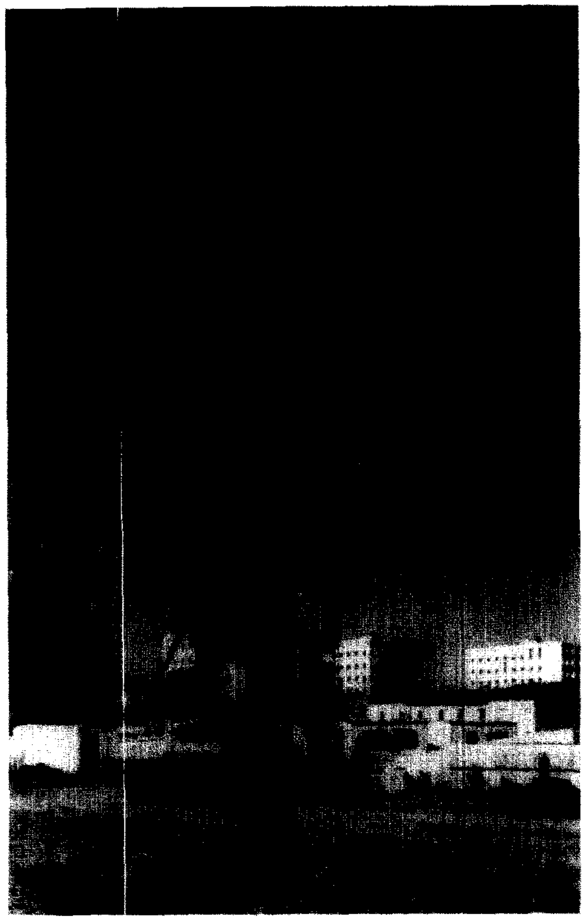

Fig. 37. Geothermal water for district heating in France. A drilling rig in a residential area.

its exploitation is reasonably short if electricity generation is possible, but still very lengthy if hot water is the only final result. It is still difficult to convince governments and investors that non-electrical uses of geothermal energy can play a significant role in the saving of high-quality fuels. The financial side of these operations is, in fact, still a major constraint in the use of natural hot water: the economic benefits generally come only after a long time, and, worse still, large investments are required from the very beginning of a project. However, in many cases the utilisation of geothermal waters in non-electrical applications can be a viable and economic option in the right conditions, and especially if fossil fuels must be imported.

FINANCIAL INVESTMENTS IN GEOTHERMAL ELECTRICAL AND NON-ELECTRICAL USES WORLDWIDE

Geothermal energy has long been a well-proven energy resource that uses mostly conventional technology. Commercial generation of electricity started in 1913 and installed

Table 9. Thermal power and flow-rates for non-electrical uses of geothermal energy worldwide in 1994. (From Ref. [45], modified)

Country	Flow-rate (kg/s)	Power (MW_t)
Algeria	550	100
Austria	173	21.1
Belgium	57.9	3.9
Bulgaria	258.5	133.1
Canada	40	1.68
China	8628	1915
Denmark	44.3	3.5
France	2889	599
Georgia	1363	245
Germany	316	32
Greece	261	22.6
Guatemala	12	2.64
Hungary	1714	340
Iceland	5794	1443
Israel	1217	44.2
Italy	1612	307
Japan	1670	319
Macedonia	761	69.5
New Zealand	353	264
Poland	298	63
Romania	792	137
Russia	1240	210
Serbia	892	80
Slovakia	353	99.7
Slovenia	581	37
Sweden	455	47
Switzerland	120	110
Turkey	700	140
U.S.A.	3905	1874
Total	**37,050**	**8664**

capacities of hundreds of megawatts, both for electrical and non-electrical uses (direct uses), had already been set up half a century ago.

Comprehensive surveys have been carried out on many geothermal issues, but until 1994 there had been no exhaustive analysis of geothermal investments worldwide. In that year, Fridleifsson and Freeston made a survey of investment data from all the main geothermal countries in the world between 1973 and 1992. Table 10 shows the geothermal investments made during 1973–1982 and 1983–1992 in various geographic regions of the world. The table includes only countries where more than 2 million US$ were invested in the two decades (1973–1992). The survey indicates the total investments to be around US$22,000 million, 7600 of which were invested during 1973–1982 and 14,300 during 1983–1992, indicating a increase in total investments of 89%. More specifically, 17,600 million US$ (80%) were invested in industrialised countries, 3500 million (16%) in developing countries, and 800 million (4%) in eastern European countries.

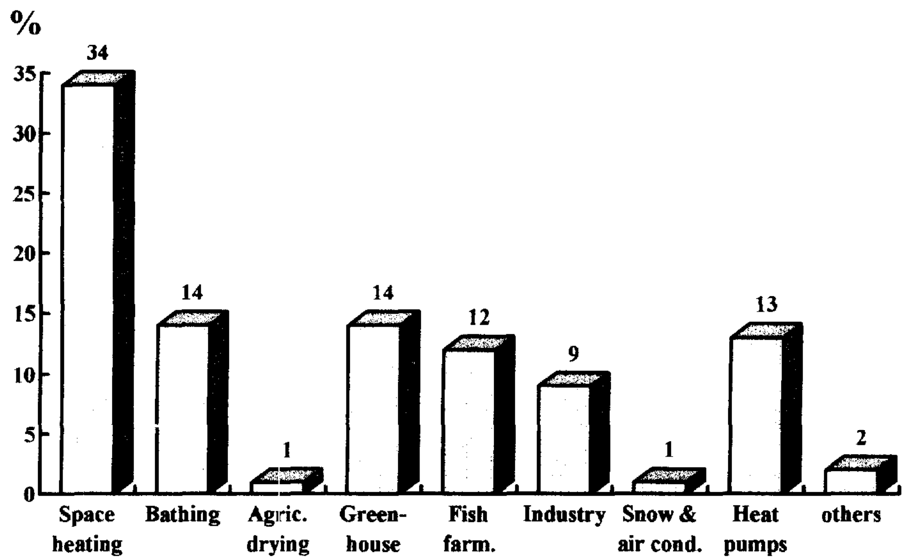

Fig. 38. Non-electrical uses of geothermal energy worldwide, annual energy utilisation by use. (From Ref. [45], modified.)

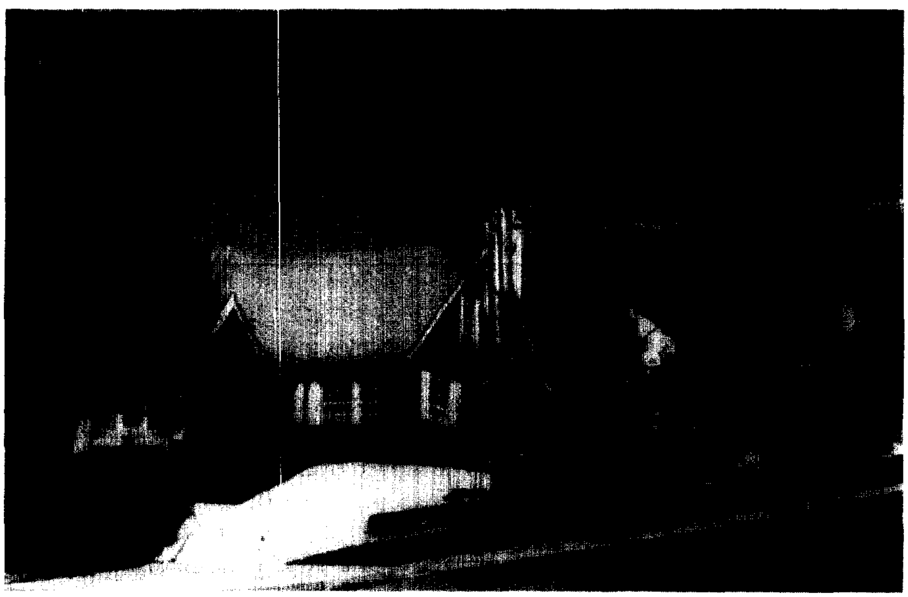

Fig. 39. Non-electrical uses of geothermal energy. Drilling of a shallow well to tap geothermal waters for domestic heating at Klamath Falls, Oregon.

The type of investment in geothermal research and development are in many ways similar to those for oil and gas, i.e. technological research and development, geothermal exploration (through geological, geophysical, and geochemical surveys), drilling, field development, power plants or plants for non-electrical uses. Geothermal projects are more site-specific than oil and gas projects as geothermal fluids are normally used at the geothermal field, or

Table 10. Estimates of investments in geothermal development worldwide in 1973–1982 and 1983–1992, in millions of US$ (1992 value). (From Ref [21], modified)

Region	Research and development	Field development	Utilisation: electric	Utilisation: non-electric	**Total (million US$)**
Africa					
1973–1982	28	31	70		**129**
1983–1992	34	78	30	1	**143**
Asia					
1973–1982	634	722	742	350	**2448**
1983–1992	1520	1488	998	752	**4758**
Latin America					
1973–1982	72	148	263	1	**484**
1983–1992	62	338	292	1	**693**
New Independent States—Central and Eastern Europe					
1973–1982	13	118	30	166	**327**
1983–1992	27	229		344	**600**
U.S.A.					
1973–1982	1178	375	750	50	**2353**
1983–1992	666	1669	2780	53	**5168**
Western Europe					
1973–1982	379	597	230	618	**1824**
1983–1992	661	1005	382	707	**2755**
Oceania					
1973–1982	22	10		2	**34**
1983–1992	12	40	160	2	**214**
Total					
1973–1982	2326	2001	2085	1187	**7599**
1983–1992	2982	4847	4642	1860	**14,331**
Grand total	**5308**	**6848**	**6727**	**3047**	**21,930**

fairly close to it. This link to the production area is not related to technological difficulties in transporting hot water or steam over distances of tens of kilometres, but to the cost of insulating the pipelines to avoid heat losses. It would be uneconomical for the modest energy content of the geothermal resource to be moved over long distances. In fact, whereas burning a kilogram of oil produces 10,000 kcal (41,800 kJ), one kilogram of the best geothermal steam will produce at most 700 kcal (3000 kJ), and one kilogram of hot water operating between 80°C (production temperature) and 30°C (discharge temperature) will yield only 50 kcal (209 kJ).

Concluding, it is clear that the level of investments in geothermal plants will be significantly affected by the evolution of oil and other energy prices, even if expert analysts such as Lynch of the Massachusetts Institute of Technology [46] predict that oil prices will stay flat for the next half century, since long-term oil shortages though often predicted are unlikely to occur. This forecast is shared by the Royal Dutch Shell Group, widely viewed as a benchmark for strategic planning, which maintains that fossil-fuel has begun a slow, steady decline, and that more than a third of the market for new electricity generation will be supplied in three to four decades from now by renewable sources [47].

The introduction of a pollution tax for the emission of CO_2 and sulphur, as recently discussed internationally, would significantly improve the economic competitiveness of geothermal energy with respect to fossil fuels (natural gas excluded) (Figs 40 and 41).

THE ENVIRONMENTAL IMPACT OF GEOTHERMAL ENERGY

Utilisation of geothermal heat entails the extraction of large volumes of steam, or steam and water (for example, 9000 t/h at The Geysers field in California, now producing 1200 MW_e only, and 3000 t/h at Larderello, Italy, 461 MW_e installed).

Geothermal fluids have a chemical content that is site-specific, and highly dependent on the rocks of each reservoir. The major environmental impact of geothermal exploitation is pollution of air and bodies of water (rivers and lakes).

Air pollution

Steam from major geothermal fields has a content of non-condensable gases (CO_2, H_2S, NH_3, CH_4, N_2, and H_2) that ranges from 2.5 to 47 g/kg of steam (Table 1). Carbon dioxide

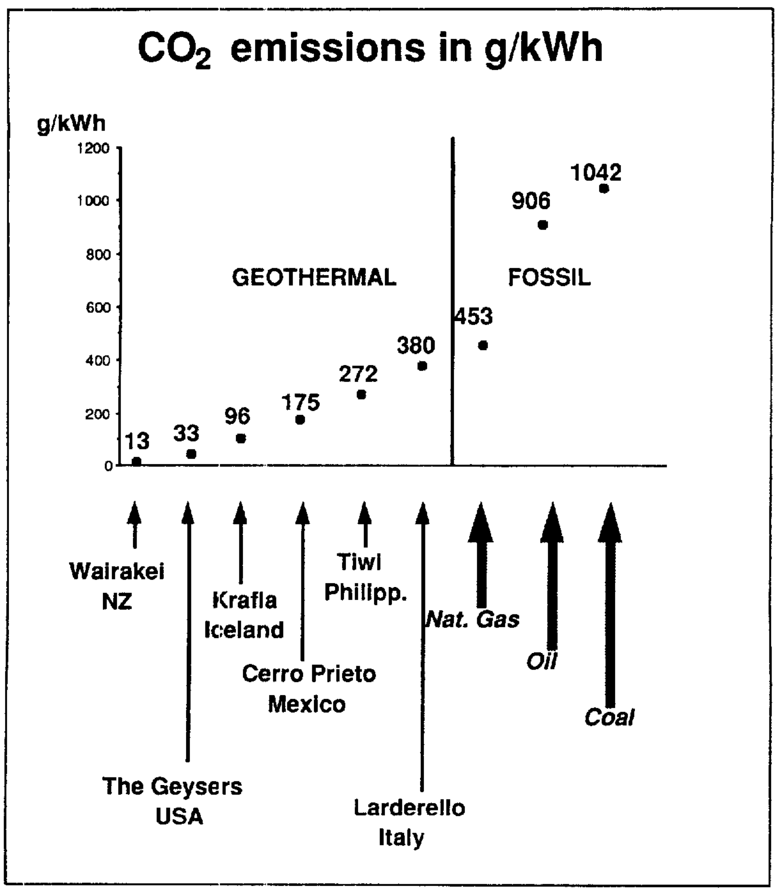

Fig. 40. Comparison of carbon dioxide emissions from geothermal and fossil fuel-fired power plants. (From Ref. [48], modified.)

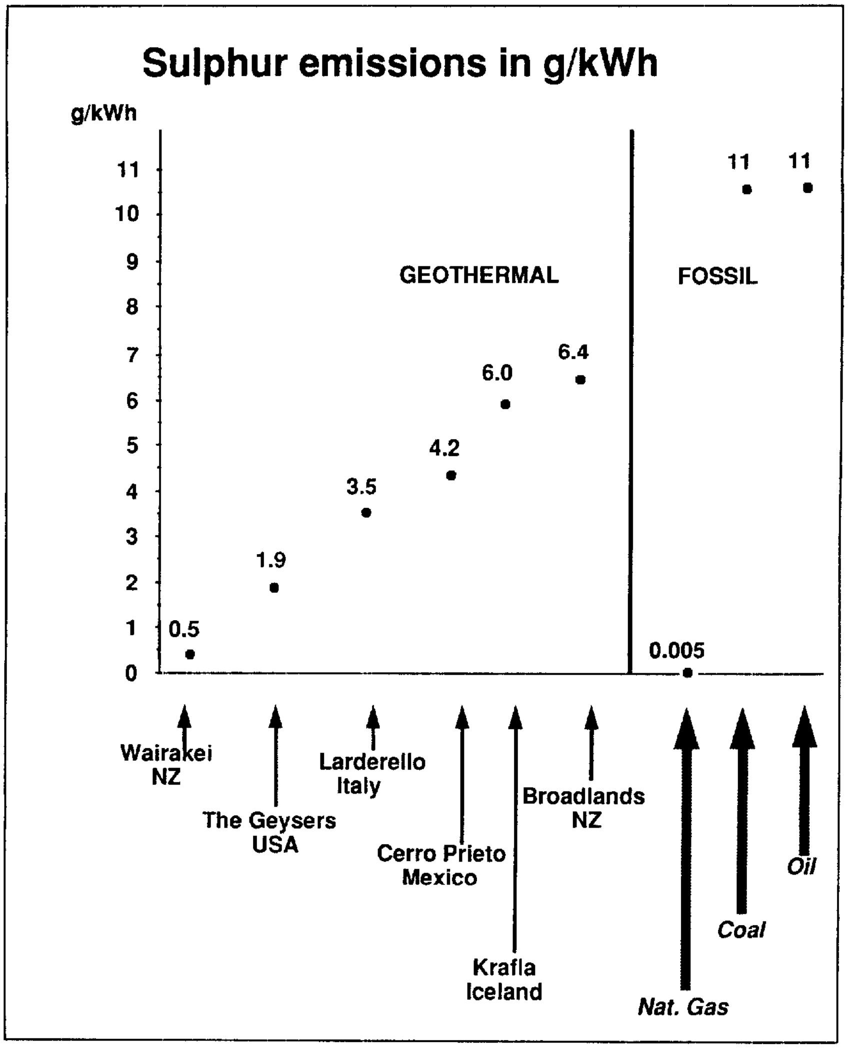

Fig. 41. Comparison of sulphur emissions from geothermal and fossil fuel-fired power plants. (Ref. [48], modified.)

is the major component, but its emission into the atmosphere is well below the figures for natural gas, oil, or coal-fired power stations per kWh generated (Fig. 40).

Hydrogen sulphide is the air pollutant of major concern in geothermal development. Its emissions generally range between 0.5 and 6.8 g/kWh. H_2S is oxidised to sulphur dioxide and then to sulphuric acid, and may cause acid rain. However a direct link between H_2S emission and acid rain has not been established [49]. Without abatement, the specific emissions of sulphur from geothermal power plants are about half those from coal-fired plants (Fig. 41).

Geothermal plants do not emit nitrogen oxides; fossil fuel plants on the contrary exhaust these toxic chemicals.

Table 11. Contaminant concentrations in selected geothermal fluids and gases, and in world average fresh water (mg/kg) (dl is the detection limit). (From Ref. [49])

	Li	B	As	Hg	H_2S	NH_3
Freshwater	0.003	0.01	0.002	0.00004	< dl	0.04
Deep well waters						
Salton Sea (U.S.)	215	390	12	0.006	16	386
Cerro Prieto (Mex)	—	19	2.3	0.00005	0.16	127
Wairakei (NZ)	14	30	4.7	0.0002	1.7	0.20
Steam (s) or non-condensable gases (ncg)						
Geysers (U.S.) (s)	—	16	0.019	0.005	540	700
Geysers (U.S.) (ncg)	—	—	—	—	222	52
Cerro Prieto (s)	—	—	—	0.04	—	—
Cerro Prieto (ncg)	—	—	—	—	350	190
Wairakei (s)	—	0.23	—	0.002	52	4
Wairakei (ncg)	—	0.052	—	—	400	7.5

Geothermal gases in steam may also contain ammonia (NH_3), traces of mercury (Hg), boron vapours (B), hydrocarbons such as methane (CH_4), and radon (Rn) (Table 11).

Boron, ammonia, and to a lesser extent mercury, are leached from the atmosphere by rain, leading to soil and vegetation contamination. Boron, in particular, can have a serious impact on vegetation. These contaminants can also affect surface waters and impact aquatic life. Geothermal literature reports that mercury emissions from geothermal power plants range between 45 and 900 μg/kWh, and are comparable with mercury emissions from coal-fired power plants. Ammonia is discharged into the atmosphere in concentrations between 57 and 1938 mg/kWh, but due to atmospheric processes it is dispersed rapidly.

Radon (^{222}Rn), a gaseous radioactive isotope naturally present in the Earth's crust, is contained in the steam and discharged into the atmosphere in concentrations of 3700–78,000 Bq/kWh [50]. At Larderello geothermal field (Italy) the radon concentration in air at ground level is 5.5 Bq/m^3 [51], and at The Geysers (California) ranges from traces to 6.0 Bq/m^3. By comparison, average levels of radon in air elsewhere are around 3 Bq/m^3. Although its levels should be monitored, there is little evidence that radon concentrations are raised above the background level by geothermal emissions.

Binary plants, in which the geothermal fluid is passed through a heat exchanger and reinjected without exposure to the atmosphere, will not discharge either gas or fluid to the environment during normal operation.

Water pollution

Water pollution of rivers and lakes is a potential hazard in power production and the management of spent geothermal fluids.

In vapour-dominated reservoirs, most of the pollutants are found in the vapour state, and the pollution of water bodies is more easily controlled than in water-dominated reservoirs. In the latter, waste steam condensate (20% of the steam supply) must be added to the waste water. The water and the condensate generally carry a variety of toxic chemicals in suspension and solution: arsenic, mercury, lead, zinc, boron, and sulphur, together with significant amounts of carbonates, silica, sulphates, and chlorides.

In water-dominated and in hot water reservoirs, water and steam (if present) are separated

at the surface (the steam is used for the generation of electricity), and the volume of water to be disposed of (which may contain large quantities of salts, even above 300 g/kg of extracted fluid) can be as much as 70 kg/kWh, more than four times the steam supply, and up to 400 kg/kWh in binary cycle plants.

Reinjection through wells drilled into selected parts of the geothermal reservoir is the most common method of disposal. Reinjection may also help to maintain reservoir pressure, to extract additional heat from the rock, and to prolong the useful life of the resource.

Reinjection might seem at first sight to be quite expensive, as it involves further wells, surface piping and continuous pumping, but the long-term effects are quite beneficial. Calculated over the entire lifetime of a geothermal project, reinjection is normally less expensive than no reinjection [21].

Land subsidence

The weight of the rocks above a reservoir of groundwater, oil, or geothermal fluids is borne in part by the mineral skeleton of the reservoir rock, and in part by fluids in the rock pores. As fluids are removed, pore pressure is reduced, and the ground tends to subside. Less subsidence is expected with harder reservoir rock.

The scale of geothermal fluid extraction is comparable to large agricultural groundwater withdrawals. A potential for subsidence is associated with geothermal development.

Water-dominated fields subside more than vapour-dominated fields. For example, the Wairakei water-dominated geothermal field in New Zealand (157 MW_e) showed 4.5 m of localised subsidence between 1964 and 1974, with the extraction of 622 Mt of fluid, and a maximum amount of 11.6 m from 1950 to 1989 [52]. The Geysers vapour-dominated field in California (now 1200 MW_e) subsided 0.14 m between 1973 and 1977 [16], and Larderello (Tuscany) also a vapour-dominated field, subsided 1.7 m between 1923 and 1986 [53].

Subsidence can be controlled or prevented by the reinjection of spent fluids. Reinjection could, however, induce microseismicity.

Induced seismicity

We have seen in earlier chapters that many geothermal reservoirs, especially at high temperature, are located in geologically unstable zones of the Earth's crust. These are zones characterised by volcanic activity, deep earthquakes, and a heat flow that is higher than the average. They are also zones with a higher frequency of naturally occurring seismic events. Water reinjection into the reservoir may induce further seismic activity by reducing rock stress, loosening vertical faults, and triggering the release of accumulated tectonic stress.

A study of the correlation between seismicity and water reinjected into the wells within a geothermal area (Larderello, Italy) suggests that a percentage of low-magnitude events are induced. However, the data also indicate that an increase in the quantity of injected water does not produce an increase in the maximum value of the magnitude of the events, but only of their number. Reinjection of waste fluids might, therefore, even have a positive effect, triggering a higher number of low-intensity shocks, but favouring the progressive, non-instantaneous release of the stress accumulated in the rocks.

Land use

Much of the land involved in geothermal field development remains usable even after full operational status is achieved.

Each 110 MW_e power plant at The Geysers (U.S.A.) requires on average 14–20 wells to

provide 700,000 kg/h of required steam supply (average 40,000 kg/h per well). The amount of land actually disturbed at The Geysers (wells, pipelines, and power plants) is 1900–3200 m^2/MW_e. Most wells are directionally drilled, so that a site of < 10,000 m^2 can accommodate five wells [16].

In Larderello, Italy, the area necessary to accommodate a 20 MW_e geothermal power plant and its ancillaries is 10,000 m^2, 1000 m^2 of which are covered by the installations [51].

Noise

Wells, newly drilled or during maintenance, have a noise level of 90–122 dB at free discharge, and 75–90 dB through silencers [16]. The pain threshold is 120 dB at 2000–4000 Hz. By comparison, a jet take-off is 125 dB at 60 m.

Solid waste

A 50 MW_e geothermal power plant may produce 24,000 kg/day of silica, if present in the reservoir rocks. This silica may have to be handled and disposed of as hazardous solid waste since it may contain Pb, Zn, and other chemical elements toxic to the environment.

ADVANCED GEOTHERMAL TECHNOLOGIES FOR THE FUTURE

Geopressured reservoirs

Geopressured reservoirs are deep reservoirs (4–6 km) in large sedimentary basins containing pressurised hot water that remained trapped at the time of deposition of the sediment, and at pressures of up to 100% in excess of the hydrostatic pressure corresponding to that depth (Fig. 42).

Geopressured fields could produce (1) the thermal energy of the pressurised hot water, (2) also hydraulic energy, by virtue of the very high pressure, and (3) methane gas. These three energy forms can also be converted to higher value forms of energy using available technologies. Thermal energy can be converted to electricity in a geothermal turbine. Hydraulic energy can be converted to electricity using a hydraulic turbine. Dissolved methane gas can be separated and sold, burned, compressed, liquefied, converted to methanol, or converted to electricity by fuelling a turbine [55].

Geopressured resources have been investigated extensively in offshore wells in Texas and Louisiana in the U.S. Gulf Coast area (deepest well 6567 m), and pilot projects were operated there for some years to produce geopressured fluid and extract its heat and methane gas content.

The U.S. Dept. of Energy has sponsored a series of geoscience studies to resolve key uncertainties in the performance potential of geopressured reservoirs.

Electrical energy conversion experiments started in the U.S., but research has still to confirm the economic feasibility and long-term use of this resource.

Hot Dry Rock systems

Hot Dry Rock (HDR) geothermal reservoirs differ significantly from conventional geothermal reservoirs, which probably exist only in the geologically favoured regions of the world shown in Fig. 3. In these regions, nature provides not only the hot rock, but also the hot water or steam.

HDR reservoirs are, instead, man-made reservoirs in rocks that are artificially fractured,

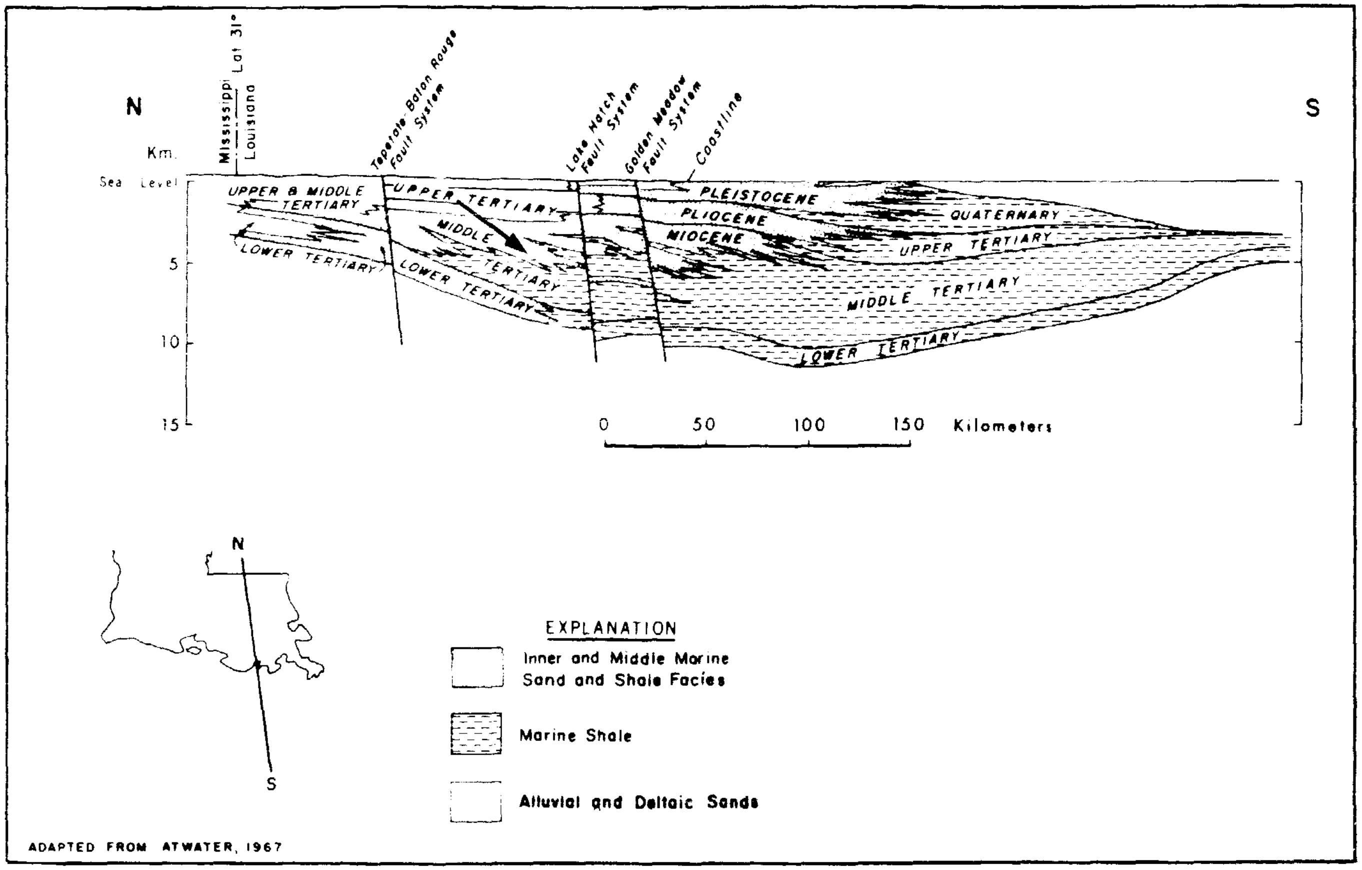

Fig. 42. Geopressured reservoirs. Geological cross-section through Louisiana and Gulf of Mexico. The arrow marks a geopressured reservoir made of a sequence of sand lenses amongst impermeable shales. (From Ref. [54].)

and thus any convenient volume of hot dry rock in the Earth's crust, at accessible depth, can become an artificial reservoir (Fig. 43).

A pair of wells is drilled into the rock, terminating several hundred metres apart. Water is circulated down the injection well and through the HDR reservoir, which acts as a heat exchanger. The fluid then returns to the surface through the production well, and thus transfers the heat to the surface as steam or hot water. Experts agree that the following key parameters, representing the lower end of the range for each, are required for a commercially viable HDR reservoir: production flow rate 50–75 kg/s; effective heat transfer area >2 million square metres; rock volume accessed >200 million cubic metres; flow losses (% of injection flow) <10% [56].

A pioneer HDR project at Los Alamos, New Mexico, U.S.A. has now reached the threshold of economic viability at a cost of 175 million US$ (1993). Since then, field experiments of various magnitudes have been undertaken in the United Kingdom, France, Germany, and Japan and, more recently, in Sweden. These experiments have been concerned with the validation of various concepts of HDR exploration. HDR systems could represent the new geothermal frontier, as there are comparatively few locations on the Earth's crust that have natural hydrothermal systems similar to those exploited at present, where heat, reservoir, and fluid are together all provided by nature.

Magma energy

The thermal energy stored in magma bodies represents a huge potential resource. The goal of the U.S. Magma Energy Extraction Program was to determine the engineering

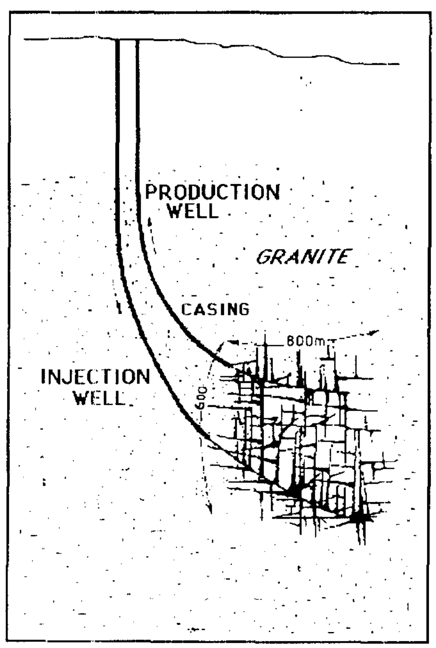

Fig. 43. Schematic representation of a hot dry rock (HDR) reservoir formed by artificial fracturing. Water is circulated down the injection well, through the HDR reservoir, and then returns to the surface through the production well as steam or hot water.

feasibility of locating, accessing, and utilising magma as a viable energy resource (Fig. 44). The first objective of the Program was to develop technology that would enable magma-generated power to be produced in the cost range of 10–20 cents/kWh by the beginning of the next century.

Realisation of this objective would require progress in four critical areas. These are (1) magma location and definition: crustal magma bodies must be located and defined in enough detail to position the drilling rig; (2) drilling: high-temperature drilling and completion technology require development for entry into magma; (3) materials: engineering materials need to be selected and tested for compatibility with the magmatic environment; (4) energy extraction: heat extraction technology needs to be developed to produce energy extraction rates sufficient to justify the cost of drilling wells into the magma bodies [57].

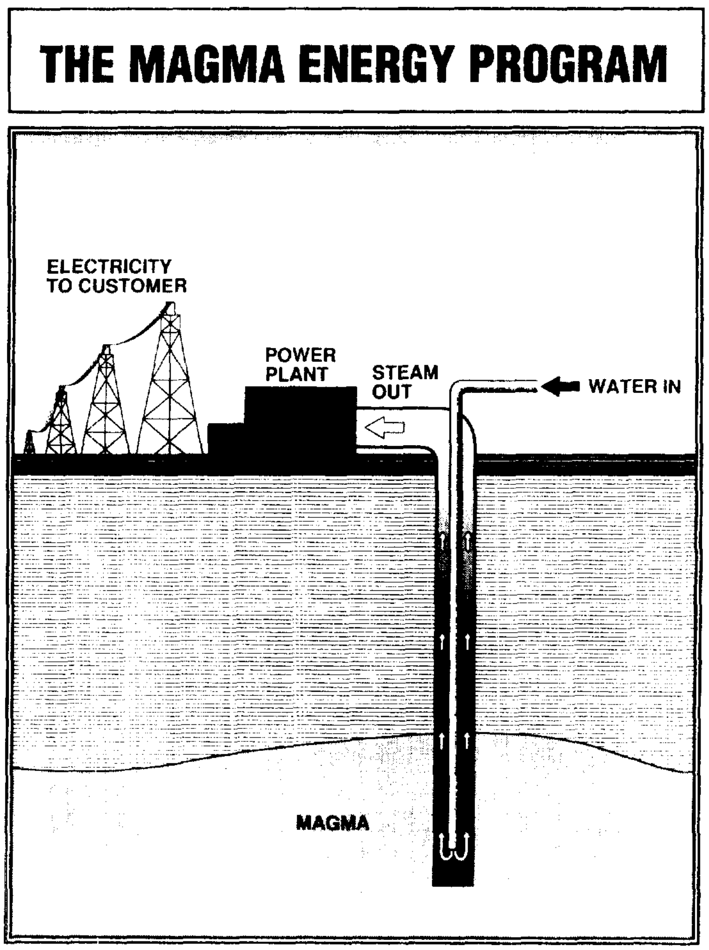

Fig. 44. Electricity from magma. Cold water is pumped into a well that reached a magma body under cooling. The produced steam could feed a power plant.

TRAINING OF GEOTHERMAL SPECIALISTS, GEOTHERMAL LITERATURE, AND GEOTHERMAL ASSOCIATIONS

Training of specialists

In 1968 it was already clear that one of the reasons for the slow progress of geothermal research, especially in developing countries, was the lack of qualified technical and scientific personnel. During that year UNESCO convened a group of experts to evaluate what steps could be taken to change this situation. The result of this action was the creation in 1970 of the first two geothermal training centres, one in Pisa, Italy, organised by the International Institute for Geothermal Research and financed by the Italian Ministry for Foreign Affairs and UNESCO, and the other in Kyushu, Japan, at the Research Institute of Industrial Science of the university, financed by the Japanese government and UNESCO. Two more training centres followed, both in 1979, one in Auckland, New Zealand, sponsored by the New Zealand government and the United Nations Development Project, and organised by the local university, and the other in Reykjavik, Iceland, a joint effort of the United Nations University and the Icelandic government.

Apart from these four centres, all operating with UN support, the Universidad Autonoma de Baja California (Mexico), in collaboration with the Comisión Federal de Electricidad and the Instituto de Investigaciones Eléctricas (both in Mexico), has been offering a full year training course in geothermal energy since 1984. Well-known and appreciated short courses are also organised regularly by the Geothermal Resources Council in the U.S.A.

Approximately 1260 specialists have been trained in the UN-sponsored courses over the last quarter of the century, and the steady rise in the geothermal installed capacity, especially in the developing countries, is a clear proof of the validity of these training initiatives.

Technical information exchange

A large number of geothermal publications are available, in the form of conference proceedings, journals, and textbooks, and newcomers to geothermal activity may be disoriented by the mass of literature in circulation, estimated at about 30,000 titles since the beginning of this century.

Obviously not all the material published is valid and useful, though often expensive. Selected titles for a basic geothermal library were suggested years ago by the geothermal training centres of Italy and Iceland [58].

Table 12 lists the journals that publish geothermal material on a regular or frequent basis. Various scientific organisations also publish, albeit irregularly, series of reports that are totally or partly dedicated to geothermal topics. The most important geothermal report series are those published in the U.S.A. by:

- Lawrence Berkeley National Laboratory, California,
- Sandia National Laboratory, New Mexico, and
- U.S. Geological Survey, with their *Professional Papers*.

Further important recent sources of geothermal information and on-line systems are the following [59]

- *Proceedings of the World Geothermal Congress* '95 (5 volumes, 3028 pages), International Geothermal Association, Taupo, New Zealand, fax +64-7-3748199; e-mail: igasec@gns.cri.nz

Table 12. Journals publishing geothermal articles

	Type of geoth. articles	Publisher
	Journals that publish *only* geothermal articles	
Geothermics	Specialised	Elsevier, U.K.
Geothermal Science and Technology	Specialised	Gordon & Breach, U.S.A.
Geotermia	Specialised	Comision. Fed. de Electricidad, Mexico
Chinetsu—J. of Japan Geoth. Energy Association	Specialised	Jap. Geoth. Energy Assoc., Japan
J. of the Geothermal Research Society of Japan	Specialised	Geoth. Research Society, Japan
Geothermal Resources Council Bulletin	General-News	Geoth. Resources Council, U.S.A.
Geo-Heat Center Quarterly Bulletin	Technological	Oregon Inst. Technology. U.S.A.
Geothermische Energie	Newsletter	Geothermische Vereinigung, Germany
IGA News	Newsletter	Internat. Geothermal Assoc., New Zealand.
	Journals that *more often* publish geothermal articles	
AAPG Bulletin	Exploration	Amer. Assoc. Petroleum Geologists, U.S.A.
Acta Geophysica Sinica	Exploration	People's Republic of China
Advances in Water Resources	Reservoir	Elsevier, U.K.
Applied Geochemistry	Theoretical	Elsevier, U.K.
Bolletino della Società Geologica Italiana	Exploration	Società Geologica Italiana, Italy
Bulletin of Volcanology	Exploration	Springer, Germany
California Geology	Newsletter	Cal. Dept. Conserv., Div. Mines & Geol., U.S.A.
Computers & Geosciences	Software	Elsevier, U.K.
Earth and Planetary Science Letters	Exploration	Elsevier, The Netherlands
Economic Geology	Exploration	Econ. Geology Publ. Co., U.S.A.
Energy Sources	General	Taylor & Francis, U.K.
Eos-Trans. American Geophysical Union	General	Amer. Geophysical Union, U.S.A.
European Journal of Mineralogy	Petrology	E. Schweizerbart'sche Verlags., Germany
Geochemical Journal	Exploration	Geoch. Society of J., Japan
Geochemistry International	Exploration	John Wiley & Sons, Russia/U.S.A.
Geochimica et Cosmochimica Acta	Theoretical	Elsevier, U.K.
Geophysical Journal International	Exploration	Blackwell, U.K.
Geophysical Prospecting	Exploration	Europ. Assoc. Geoexplor. Geophysicists, U.K.
Geophysical Research Letters	Exploration	Amer. Geophysical Union, U.S.A.

Geophysics	Exploration	Soc. Exploration Geophysicists, U.S.A.
Geotimes	General	Amer. Geological Institute, U.S.A.
Hydrogéologie	Exploration	BRGM, France
International Journal of Energy Research	General	John Wiley & Sons, U.K.
Izvestya—Physics of the Solid Earth	Exploration	Amer. Geophysical Union, Russia/U.S.A.
Journal of Applied Geophysics	Exploration	Elsevier, The Netherlands
Journal of Geochemical Exploration	Exploration	Elsevier, The Netherlands
Journal of Geodynamics	Theoretical	Elsevier, U.K.
Journal of Geophysical Research	Exploration	Amer. Geophysical Union, U.S.A.
Journal of Hydrology	Reservoir	Elsevier, The Netherlands
Journal of Petroleum Technology	Reservoir	Soc. Petroleum Engineers, U.S.A.
Journal of Physics of the Earth	Theoretical	Center for Academic Publications, Japan
Journal of Volcanology and Geothermal Research	Exploration	Elsevier, The Netherlands
Nature	Theoretical	Macmillan, U.K.
New Scientist	General	Holborn Publ. Group, U.K.
New Zealand Journal of Geology and Geophysics	Exploration	SIR Publishing, New Zealand
Nonrenewable Resources	General	Plenum Press, U.S.A.
Physics of the Earth and Planetary Interior	Theoretical	Elsevier, The Netherlands
Revue de l'Institut Français du Pétrole	Exploration	Institut Français du Pétrole, France
Science	General	Amer. Assoc. Advanc. of Science, U.S.A.
Scientia Geologica Sinica	Exploration	Chinese Academy of Sciences, China
Scientific Drilling	Technological	Springer, Germany
SPE Formation Evaluation	Reservoir	Soc. Petroleum Engineers, U.S.A.
SPE Production & Facilities	Reservoir	Soc. Petroleum Engineers, U.S.A.
SPE Reservoir Engineering	Reservoir	Soc. Petroleum Engineers, U.S.A.
Studia Geophysica et Geodaetica	Exploration	Geophys. Inst., Acad. of Sci., Czech Republic
Technika Poszukiwan Geolog.-Geosyn. i Geot.	Exploration	Polish Acad. of Sciences, Poland
Tectonophysics	Exploration	Elsevier, The Netherlands
Terra Nova	Exploration	Blackwell, U.K.
Transport in Porous Media	Reservoir	Kluwer, The Netherlands
Volcanology and Seismology	Exploration	Acad. of Sciences, Russia
Water Resources Research	Reservoir	Amer. Geophys. Union, U.S.A.

- *Proceedings of the Annual Meeting of the Geothermal Resources Council, GRC Transactions*, fax +1-916-7582839; e-mail: geores@wheel.dcn.davis.ca.us
- *Proceedings of the Geothermal Reservoir Engineering Workshops*, Dept. of Petroleum Engineering, Stanford University, California, fax +1-415-7252099; e-mail: shaun-@pangea.stanford.edu
- *Proceedings of the New Zealand Geothermal Workshops*, Geothermal Institute, University of Auckland, New Zealand, +64-9-3737436; e-mail: thermal@auckland.ac.nz
- *Energy, Science and Technology Database* (U.S.A.) at: http://apollo.osti.gov/html/osti/ostipg.html
- *Energy Efficiency and Renewable Energy Network* (U.S.A.) at: http://www.osti.gov/html/eren/eren.html
- *Geothermal Resources Council On-line Information System* (U.S.A.), e-mail contact: geores@wheel.dcn.davis.ca.us
- *Solstice—Center for Renewable Energy and Sustainable Technology* (CREST, U.S.A.), at: http://solstice.crest.org
- *International Geothermal Association*, at http://www.demon.co.uk/geosci/igahome.html
- *THERMIE—European Union Energy Technology Program*, at: http://www.ib.be./thermie
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National and international geothermal associations

Local initiative in some countries has led to the creation of national geothermal associations with the general objective of encouraging research, exploration and development of geothermal energy.

The largest and best known of these national geothermal associations is the Geothermal Resources Council, an educational association based in Davis, California, and founded in 1972. The Council is a membership organisation with about 1000 individual and collective members. It is very active in the dissemination of information through its excellent and up-to-date publications, educational programs, and annual geothermal meetings.

Other, younger national associations have emerged in Canada, Georgia, Germany, Indonesia, Japan, Lithuania, Mexico, New Zealand, Poland, Romania, Russia, and Switzerland. In the U.S.A. apart from the Geothermal Resources Council, there are associations devoted to the development of specific tasks or local geothermal resources. These include the Geothermal Energy Association, the Geysers Geothermal Association, the Geothermal Association of Imperial County, and the Geothermal Education Office. Japan also has the Geothermal Research Society of Japan, based at the Geological Survey of Japan in Tsukuba.

The International Geothermal Association (IGA) was created in 1988 by the joint efforts of a group of geothermal experts from a number of countries.

The concept of a non-political, non-governmental, non-profit organisation, designed to operate worldwide, dates back almost 25 years, and has been discussed informally on several occasions during subsequent geothermal meetings. Although many were convinced of the merits of the basic concept, for a number of practical reasons the association was unable to take practical form.

Finally, through the renewed initiative of the Geothermal Resources Council of the U.S.A., and the international geothermal training centres, and ad hoc committee was set up in 1987 and the IGA finally established and registered in Auckland, New Zealand.

The International Geothermal Association is:

- a broad, open forum for the discussion and debate of problems of common interest;
- a focus for the evaluation of actions and means necessary to strengthen the human capabilities needed for accelerated research, development, and application of geothermal resources;
- a vehicle for the encouragement and implementation of activities necessary to accelerate the utilisation of geothermal resources around the world;
- a reference point for geothermal-related activities in which the international geothermal community is involved.

Ten of the above-mentioned national associations are at present affiliated members of the International Geothermal Association, whose membership, regardless of type of affiliation and membership category consisted of 1960 members at the end of July 1996 [60].

CONCLUSIONS

The utilisation of geothermal resources, i.e. of the Earth's internal heat, is probably as old as mankind itself. However, only at the beginning of this century did we begin to understand the geothermal phenomenon, and why it occurs in certain areas.

It is probably evident from this paper that the search for and the use of the Earth's heat, especially on an industrial scale, is a multidisciplinary activity, implying the interaction of the Earth sciences with engineering and economics. This interaction is perhaps one of the reasons for the scarce information of what geothermal energy is, and how beneficial its uses can be. The general public is largely unaware, even now, of what geothermal energy is, or even of the meaning of the term "geothermal". A few will hazard a guess that geothermal energy has something in common with volcanoes, which is partly true; very few are aware that geothermal resources can be a source of energy; and even fewer know that electricity has been produced for about a century on an industrial level by this non-conventional source, with power plants totalling more than 7000 MW_e spread worldwide, a capacity that is almost twice as large as the electric capacity of wind, solar, and tidal sources taken together. Nor is this ignorance confined to the general public, as the subject of geothermal energy outside the small group of experts, will often raise blank looks even today in many university science departments.

The interaction of the two main fields of geology and engineering is partly accountable for the lack of knowledge about geothermal energy. Geologists, who know all about the Earth's heat and its possible uses, are in difficulty when tackling the technological side. On the other hand, engineers, who have the technology at their fingertips, have a poor knowledge of the Earth's interior.

It should be added that the energy experts that discuss renewable sources are normally engineers, physicists, or economists, whose expertise is far from the Earth sciences, and they are often unaware that our planet besides the well-known fossil fuels, also conceals another resource of industrial significance, i.e. geothermal energy.

A further reason for the lack of confidence in geothermal energy amongst those working

in the field of exact sciences is the uncertainty that accompanies anything that is concealed in the underground and has to be brought to the surface, especially if it is at depths of kilometres. Geologists call this uncertainty "mining risk", sometimes high, always unpredictable. This risk is understandably not welcomed by engineers, economists, and public officers, whose duty is to find a supply of energy from sources available with certainty and possibly stable in price and in time. Furthermore, weighing the scales even further against geothermal energy is the fact that its exploitation requires expensive wells and surface installations such as pipes, heat exchangers, pumps, etc., all of which prevent its use at a family level, as opposed to solar collectors, installed on the roofs of houses by the sea or in the mountains, or with small wind turbines so common in small farms. Exploitation of the geothermal resource is, with few exceptions, an industrial activity requiring investments that are beyond the reach of a single family or even a small village.

Geothermal energy is not available everywhere, especially the resources needed for production of electric energy. However, this is not so big a drawback nowadays, when many countries have their own national grid, and electricity production can take place anywhere in the country. Unfortunately, however, not many regions are endowed with the necessary geological conditions for the production of geothermal electricity on an industrial scale. It will certainly be possible in the near future to locate new geothermal fields (hydrothermal), but the contribution of geothermal energy to the electric demand will never be significant in the industrialised countries. This is not true of developing countries where a significant percentage of their electricity capacity could still be supplied from geothermal resources, in some cases more than 15% of the total electricity produced in the country.

Despite these drawbacks, it is a fact that the geothermal kWh is generally cost-competitive with conventional sources, and produced by means of well-proved conventional technology. Geothermal energy is reliable, and indeed has been used to heat large municipal districts for more than 60 years, as well as to feed power plants of thousands of megawatts of electricity for more than a quarter of a century, and of hundreds of megawatts for more than half a century.

The non-electrical uses of natural thermal waters, which can be found almost anywhere in the world, could certainly be expanded were governments to offer suitable, flexible, and timely incentives. Furthermore, more information is needed on this source of energy, targeted at policy-makers, especially on a local level, and particularly as regards the environmental benefits attainable from this sustainable and benign form of energy.

At the moment, non-electrical geothermal applications are not particularly cheap compared to fossil fuels, but their convenience lies both in the possibility of saving conventional fuels for the high-temperature uses (and oil for petrolchemistry), and in replacing imported fossil fuel, which has to be paid for in hard foreign currency, with a national energy, machinery and workforce.

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